

Research Article

Paleoclimate changes and ecosystem responses of the Bulgarian Black Sea zone during the last 26000 years

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Abstract

Multi-proxy analysis (spore-pollen, dinoflagellate cysts, other non-pollen palynomorphs (NPPs), radiocarbon dating and lithology) was performed on marine sediments from three new cores retrieved during the two cruise expeditions on board the Research Vessel “Akademik” in 2009 and 2011. The Varna transect comprises three cores extending from the outer shelf, continental slope and deep-water zone. The record spans the last 26000 years (all ages obtained in this study are given in calendar years BP (cal. yrs BP)). The pollen record reveals the spreading of steppe vegetation dominated by *Artemisia* and *Chenopodiaceae*, suggesting cold and dry environments during the Late Pleniglacial – Oldest Dryas (25903–15612 cal. yrs BP). Stands of *Pinus* and *Quercus* reflect warming/humidity increase during the melting pulses (19.2–14.5 cal. ka BP) and the Late Glacial interstadials Bølling and Allerød. The Younger Dryas (13257–11788 cal. yrs BP) coldest and driest environments are clearly demonstrated by the maximum relative abundance of *Artemisia* and *Chenopodiaceae*. During the Early Holocene (Preboreal and Boreal chronozones, 11788–8004 cal. yrs BP), *Quercus* appeared as a pioneer species and, along with other temperate deciduous arboreal taxa, formed open deciduous forests as a response to the increased temperature. The rapid expansion of these taxa indicates that they survived in Glacial refugia in the coastal mountains. During the Atlantic chronozone (8004–5483 cal. yrs BP), optimal climate conditions (high humidity and increased mean annual temperatures) stimulated the establishment of species-rich mixed temperate deciduous forests. During the Subboreal chronozone (5483–2837 cal. yrs BP), *Carpinus betulus* and *Fagus* expanded simultaneously and became more important components of mixed oak forests and probably also formed separate communities. During the Subatlantic chronozone (2837 cal. yrs BP to pre-industrial time), climate-driven changes (an increase of humidity and a cooling of the climate) appear to be the main drivers of the specific vegetation succession expressed by increased abundance of *Alnus*, *Fraxinus excelsior* and *Salix* along with lianas, suggesting formation of flooded riparian forests (so called ‘Longoz’) lining the river valleys along the Black Sea coast. The first indicators of farming and other human activities have been recorded since 7074 cal. yrs BP. The dinoflagellate cyst (dinocyst) assemblages have been analysed to assess the changes in the Black Sea environment over the last 26000 years in terms of fluctuation in paleoproduction and surface water conditions related to changes in climate, freshwater input and Mediterranean water intrusion. Two major dinocyst assemblages were distinguished: one dominated by stenohaline freshwater/brackish-water species and a successive one dominated by euryhaline marine species.

The changes in the composition of the assemblages occurred at 7668 cal. yrs BP. The abrupt decrease of stenohaline freshwater/brackish-water species *Pyxidinosia psilata* and *Spiniferites cruciformis* was followed upwards by a gradual increase in euryhaline marine species, such as *Lingulodinium machaerophorum*, *Spiniferites belerius*, *S. bentonii* and acritarch *Cymatiosphaera globulosa*. The first occurrence of euryhaline marine species took place synchronously with the onset of sapropel deposition. Modern marine conditions were established after 6417 cal yrs BP when an abundance of Mediterranean-related species, such as *Operculodinium centrocarpum* and *Spiniferites mirabilis*, along with other heterotrophic species, occurred. After the stable cold and dry environment during the Last Glacial Maximum, the phytoplankton record of core AKAD 11-17 shows that *Pediastrum boryanum* var. *boryanum* has a cyclical abundance associated with the deposition of four red-brown clay layers between 19.2 and 14.5 cal. ka BP. This event is associated with the major melting phase of European Ice drained by the Danube and Dnieper Rivers in response to climate warming observed after the end of the Last Glacial Maximum. During the Early Holocene, *P. psilata*, characterised by a preference to warmer temperatures, demonstrates its ecological optimum for growth concerning SST reaching maximum relative abundance of 94% between 11072 and 8638 cal. yrs BP. This maximum was interrupted by an abrupt significant short-term decrease in the relative abundance of *P. psilata* centred between 8500 and 8300 cal. yrs BP reflecting cold conditions similar to those of Younger Dryas. This finding, also confirmed by the rapid significant decrease of arboreal pollen, particularly of *Quercus* in the same studied core, is considered a regional expression of the well-known '8.2 ka cold event' which is commonly linked to a meltwater-related perturbation of the Atlantic Meridional Overturning Circulation (AMOC) and associated collapse of oceanic northward heat transport. Our fossil pollen and dinocyst data confirm that the high amplitude temperature anomaly associated with 'the 8.2 ka cold event' may have also occurred in south-eastern Europe, at lower latitudes of the western Black Sea coastal area, most probably due to atmospheric transition and/or river discharge.

Key words: Dinoflagellate cyst, non-pollen palynomorphs, radiocarbon dating, spore-pollen analysis

Introduction

The Black Sea, as an almost isolated marginal sea, is particularly sensitive to paleoenvironmental changes and, therefore, Black Sea sediments provide an excellent opportunity for high-resolution studies of past climatic, vegetation, human activity and hydrological changes in the catchment (Bahr et al. 2005). In contrast to shelf records which are affected by erosion during lowstands, pollen and dinocyst records from the continental slope and deep water Black Sea cores are of particular interest as they can provide almost uninterrupted sequences covering the Late Pleistocene and Holocene and can be used to obtain an independent record of regional climate change and land-based interpretation of the reconstructed vegetation and paleohydrological regime. These reconstructions are able to describe the interaction between climate and vegetation and also to clarify the role of coastline and other geomorphological changes, salinity and impacts of human activities in the Black Sea region (Cordova et al. 2009).

The Black Sea sediments have been intensively investigated by multi-proxy analysis during the last five decades. The biostratigraphic investigations of

Quaternary marine sediments taken by the Scientific-Research vessels “Atlantis-2” and “Glomar-Challenger” established a baseline chronostratigraphy. Palynological investigations of sediments from the deep-water zone allowed Traverse (1974, 1978a, 1978b), Koreneva and Kartashova (1978) and Koreneva (1980) to outline the stratigraphy of sediments, vegetation dynamics and climate changes along the Black Sea coast from the end of the Pliocene through the Pleistocene at a very low resolution of tens of thousands of years. The first detailed marinopalynological investigations of the western Black Sea shelf are those of Roman (1974), Bozilova et al. (1979) and Komarov et al. (1979). Based on marinopalynological data of the western Black Sea sediments, the climatic changes during the Late Glacial and Holocene were estimated and considered to be the main drivers for vegetation changes along the Bulgarian Black Sea coast (Shimkus et al. 1977; Komarov et al. 1978; Bozilova et al. 1979; Chernyishova 1980; Filipova and Dimitrov 1987; Atanassova 1990, 1995, 1999, 2005; Atanassova and Bozilova 1992; Mudie et al. 2007). Palaeoecological changes during the Quaternary and possible sea-level fluctuations during the Holocene were traced by Filipova-Marinova (2003a, 2003b, 2007); Filipova-Marinova and Christova (2004), Filipova-Marinova et al. (2004) and Hiscott et al. (2007). Mudie et al. (2007) showed that organic-walled microfossils including pollen, spores and dinocysts are well-preserved and abundant in deep-water Pleistocene and Holocene sediments. These authors presented pollen assemblages for the last 33000 years and reported the first high resolution Holocene pollen influx data for the SW Black Sea shelf. Filipova-Marinova et al. (2013) reported the first high-resolution palynostratigraphy of Late Quaternary sediments and the chronologically defined vegetation stages with their specific features, particularly a short-term cooling of the Holocene climate, associated with the ‘8.2 ka cold event’ identified for the first time in marine records from the central Bulgarian Black Sea area. Vegetation and environmental dynamics in northern Anatolia during the last 18000 years are reconstructed using multi-proxy records from the southern Black Sea shelf (Shumilovskikh et al. 2012). Mudie et al. (2002) showed the close correlation between marine pollen assemblage zones in the Marmara and southern Black Sea with lakes in northern Turkey and Bulgaria. Quantitative paleovegetation reconstruction and correlation of pollen data of 99 sequences from the Black, Marmara and Azov Seas are presented by Cordova et al. (2009). First palynostratigraphy of western Black Sea sediments was proposed by Filipova-Marinova (2006a), based on 12 representative cores.

The pioneer work of Wall et al. (1973) enabled the use of dinocysts as potential paleoceanographic proxies. Since the 1980s, numerous studies from the Black Sea permitted the definition of distribution patterns in regional levels and have led to determination of the relationship between dinocyst assemblages and sea surface water conditions (De Vernal et al. 1994; Marret 1994; Matthiesen 1995; Mudie and Harland 1996; Mudie et al. 2001; Mudie et al. 2002; Marret and Zonneveld 2003; Marret et al. 2009; Mertens et al. 2012). The studies of van Geel (2001), Brenner (2001), Mudie et al. (2002) and Marret et al. (2009) describe non-pollen palynomorphs (fungal spores and remains of hyphae) as important markers of salinity, nutrient loading and human activity, including ballast discharge, farming and soil erosion. Mudie et al. (2002) and Marret et al. (2009) consider fungal remains as an index of terrigenous sediment influx and transport by large rivers. The Late Quaternary history of connection of the

Black Sea to the eastern Mediterranean, especially the timing and conditions during the Holocene transition of the Black Sea from freshwater/brackish-water to marine has been intensively debated: Ryan et al. (1997, 2003), Aksu et al. (2002), Major et al. (2002), Bahr et al. (2005, 2006), Hiscott et al. (2007), Yanko-Hombach (2007); Londeix et al. (2009), Marret et al. (2009), Verleye et al. (2009) and Herrle et al. (2018). In addition to the Holocene connection with the Marmara Sea, the Black Sea experienced a period of connection to the Caspian Sea when meltwater from Scandinavian ice sheets raised the water level of the Caspian Sea over the Manych depression. This period is documented in the Black Sea by the deposition of a series reddish-brown clay layers (Major et al. 2002; Bahr et al. 2005, 2008).

Recent studies in the western Black Sea are focused mainly on palaeoecological changes during the Late Glacial and Holocene. There is a lack of uninterrupted Late Quaternary sediments from the northern Bulgarian Black Sea area adjacent to Varna. Therefore, in order to obtain appropriate records which would allow a better more detailed description of the pollen and dinocyst stratigraphy and more precise palaeoecological reconstructions of the Bulgarian sector of the Black Sea, two expeditions by the Research Vessel “Akademik” in 2009 and 2011 were carried out. A total of 105 new samples were taken for multi-proxy analysis of sediments from three representative cores: AKAD 11-17 (deep-water zone, water depth: 1805 m, core length: 228.5 cm), AKAD 09-10 (zone of the continental slope, water depth: 1000 m, core length: 240 cm) and AKAD 09-15 (outer shelf zone, water depth 164 m, core length 377 cm).

The aim of this study is to establish the palaeoclimatic, palaeohydrological and environmental dynamics of the Bulgarian Black Sea coastal area during the Late Pleistocene and Holocene, as well as to evaluate the timing and extent of the passage between various events previously described in other studies, based on multi-proxy analysis.

Regional setting

Present-day Oceanography of the Black Sea

The Black Sea (Fig. 1) is located between south-eastern Europe and Asia. It has an area of approximately 432,000 km² and a maximum water depth of 2258 m. It is the largest semi-enclosed inland basin in the world, where the deep-waters and surface waters are not mixed (Nikishin et al. 2003; Murray et al. 2007). The oxygenated surface layer overlies an anoxic deeper layer with elevated H₂S concentrations up to 380 µM (Murray et al. 2007). The Black Sea has an extremely large drainage basin of more than two million km², collecting the water from almost all the European countries, except the westernmost ones. The hydrologic configuration of the Black Sea is controlled by basin bathymetry and also by fluvial inputs from the discharge of the largest European rivers including the Danube, Dnieper, Dniester and the Southern Bug. Ukrainian rivers Dnieper, Southern Bug and Dniester contribute about 65 km³/yr and the Danube River is with a mean water discharge of about 200 km³/yr (Panin 2008). These inputs, plus those from smaller rivers from the Bulgarian and north Turkish margin, create a surface low salinity layer across the whole of the Black Sea. The net freshwater input to the Black Sea is about 300 km³/yr and derives from the riv-

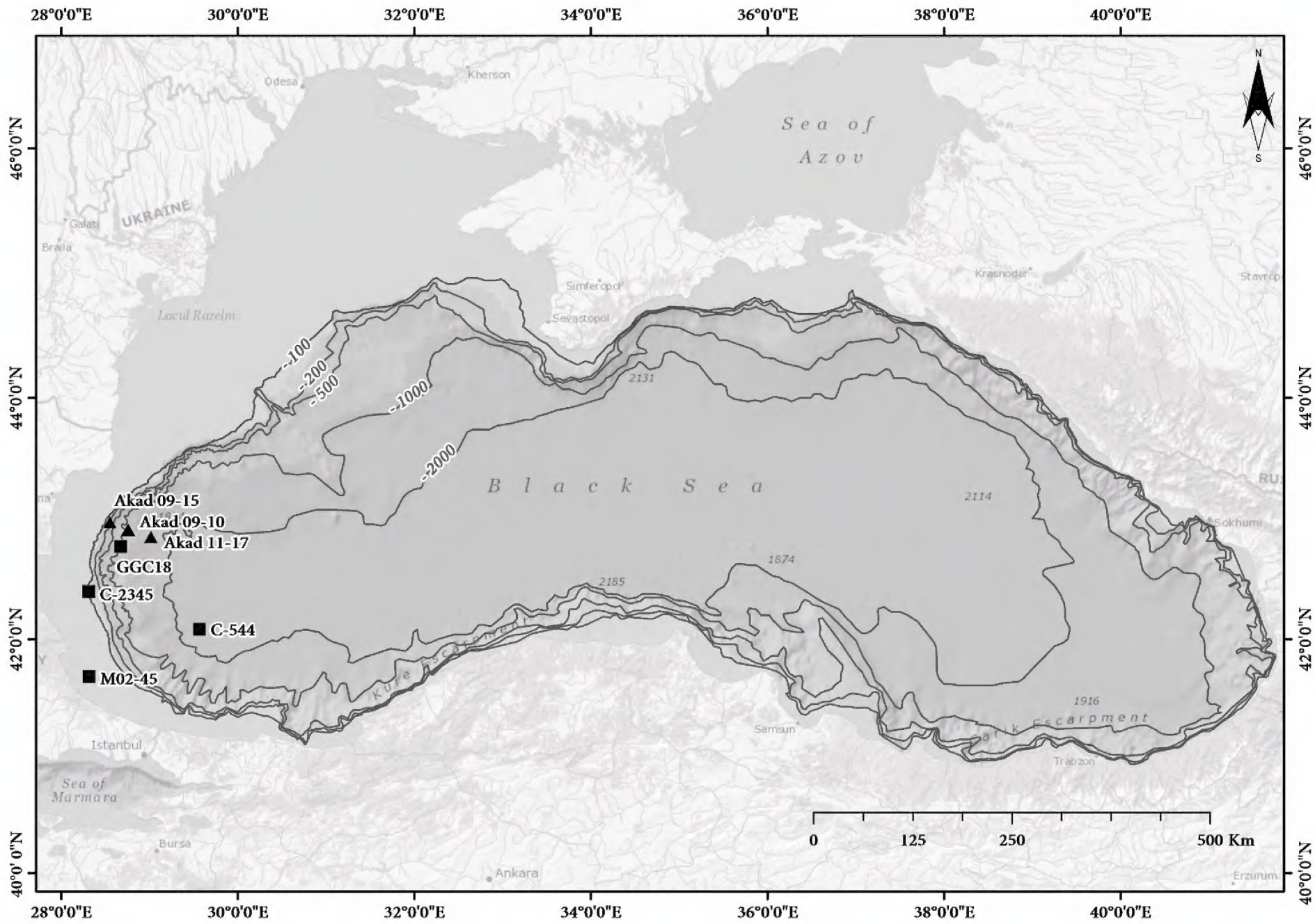


Figure 1. Location of the studied cores (black triangle) AKAD 11-17, AKAD 09-10 and AKAD 09-15 and four reference cores (black square) discussed.

er input plus precipitation. The Black Sea is presently connected to the Global Ocean through the narrow and shallow Bosphorus and the Dardanelles Straits that limit the salinity and oxygen provided to the Black Sea (Özsoy et al. 1994; Kerey et al. 2004). In addition to this marine connection, the Black Sea currently also has connection with the freshwater Sea of Azov through the narrow Strait of Kerch that has a constant outflow of waters to the Black Sea (Kosarev et al. 2007). The water exchange occurs between the Black and Marmara Seas via the Bosphorus Strait as a two-layer water flow (Özsoy et al. 1994). About 600 km³/yr cooler (5–15 °C) and less saline (18–20‰) water mass flows out of the Black Sea through the Bosphorus Strait and, from there, through the Sea of Marmara into the Dardanelles Strait as a surface outflow into the Mediterranean (Özsoy et al. 1995). This surface outflow is compensated by about 300 km³/yr of warmer (15–20 °C) and more saline (38–39‰) mixed Marmara and Aegean Sea waters that flow into the Black Sea through the Bosphorus as a deep in-flow. This produces a density-stratified water column due to the largely varying salinities entering the region. The surface layer 0–50 m is well oxygenated, while the deeper water layer 100–2243 m is highly anoxic and rich in sulphides. The approximate permanent location of the halocline is 50 to 200 m (Murray et al. 2007). Today, the surface water circulation in the Black Sea consists of two large cyclonic (counterclockwise) central gyres that define the eastern and western basins. The gyres are bounded by the wind-driven ‘Rim current’ that

flows along the edge of the continental shelf and above the continental slope around the whole basin (Oguz et al. 1993). Data from autonomous profiling floats have shown currents typically have a velocity of 15 cm/s at 200 m depth along the ‘Rim Current’ jet around the basin. At depths of 750 m and 1500 m, current velocities of 5 cm/s have been recorded with the deeper current closely following the topography along the southern margin of the Black Sea. Outside the Rim Current, numerous quasi-permanent coastal eddies are formed as a result of upwelling around the coastal apron and “wind curl” mechanisms.

Sedimentology of the Black Sea

The most recent pelagic sediment layers in the Black Sea can be divided into three units:

- Unit I is represented by micro-laminated sediments, rich in plankton-derived carbonates finely laminated coccolith-bearing ooze. The calcareous material is derived from marine coccolithophorid *Emiliania huxleyi*, which have formed part of the Black Sea plankton since 2700 years BP (Jones and Gagnon 1994). Blooms of *E. huxleyi* still occur in the Black Sea each year during late spring and summer. This unit was deposited in oxygen-depleted bottom waters.
- Unit II sediments contained micro-laminated sapropels, deposited under anoxic marine conditions between 2720 ± 160 ^{14}C yrs BP and 7540 ± 130 ^{14}C yrs BP. The base of the sapropel has been dated to 7540 ± 130 ^{14}C yrs BP in cores running in depth from 400 to 2200 m suggesting that anoxia developed at the same time throughout the interior Black Sea (Jones and Gagnon 1994). The onset of Unit II is characterised by the occurrence of finely-laminated layers rich in aragonite crystals (Ross and Degens 1974; Jones and Gagnon 1994; Soulet et al. 2011) and by a sharp increase in Total Organic Carbon (Bahr et al. 2008).
- Unit III sediments are older than 7540 ± 130 ^{14}C yrs BP and were deposited when the Black Sea was a freshwater to brackish lake and are characterised by a mix of organic-poor clays and silts (Izdar and Ergün 1991; Hay et al. 1991). Unit III sediments have organic contents < 1%. Sediments consist of homogenous mostly centimetre-scale laminated muddy clay deposited under lacustrine conditions.

Geomorphology of the Bulgarian sector of the Black Sea

The large continental shelf in the north-western Black Sea narrows in the southerly direction. On the basis of the relief, shape, time of formation, character and speed of sedimentological processes, three geomorphological zones can be outlined in the western Black Sea shelf: littoral or inner, central and peripheral or outer (Dimitrov 1979). The littoral zone is considered to be of Holocene age. It extends from the coast to a depth of 20 to 50 m of the central part of the Bulgarian Black Sea coastal area. Active wave impact, erosion and accumulation are characteristic processes for this zone (Khrischev 1984). The littoral zone is separated from the central one by a depression 17–20 m deep on the northern Black Sea shelf and 65–70 m deep on the southern Bulgarian Black Sea shelf.

The central zone lies between 50 and 72 m in depth. Within it, three subzones run parallel to the coast: an inner depression, an area of depositional bars and a depositional plain. This zone experiences a high sedimentation rate, typically about 2.5 m/kyr (Khrischev 1984). The peripheral zone extends to depths between 90 m and 120 m. It is subdivided into an outer depression and an area of barrier bars and its low sedimentation rate is due to sediment removal by strong bottom currents (Dimitrov 1979). The north-western Black Sea shelf is covered only by a very thin blanket of Holocene sediments and, in some parts, the Holocene layers are completely absent due to the strong ($> 50 \text{ cm.s}^{-1}$) cyclonic 'Rim current' (Oguz and Besiktepe 1999) which transports most of the suspended sediments alongside the coast to the south (Panin et al. 1999).

According to the general morphostructural plan of the Black Sea deep-water basin, the continental slope covers 25% of its surface. The transition of the shelf to the continental slope is gentle and has a convex-up profile. The continental slope of the Bulgarian Black Sea zone is characterised by deeply-indented relief including land-sliding complexes, fault slopes, ledges and submerged valleys and canyons. Nine systems of submerged valleys are established in the area (Alexiev 2002). The transition from the continental slope to the deep basin increases in the western Black Sea from 1100 m in the north to 2000 m in the south.

The continental foot is formed by the confluence of the sedimentation materials of the submerged delta valleys. The gentle transition of the steep continental slope to the abyssal plain is accomplished by its slightly undulating plain surface. The formation of the modern shape of the continental slope took place mainly during the Pleistocene. The large input of terrestrial sediments that are the main constructive material for the continental foot was disrupted by the breaking-off access of the coastal rivers to the outer zone of the continental slope during the Holocene. The limit between the continental foot and the abyssal plain is difficult to be located. However, the isobaths 2000–2100 m localise a typical abyssal plain which declines slightly towards the deepest part of the Black Sea Basin. The abyssal plain is the earliest formed morphological element of the Black Sea (Alexiev 2002).

Climate

According to Velev (2002), the Bulgarian Black Sea coast belongs to the Continental-Mediterranean climatic area and is influenced by three different climatic regimes. Climate in the northern part and the Eastern Danube lowland is affected by strong continental influences. Prevailing winds are northeasterly and mean annual precipitation is about 450–500 mm, with a maximum in June and a minimum in February. Mean January temperature is around 0 °C, dropping to -2 °C inland. In the south, the climate is transitional Mediterranean. Mean annual precipitation is estimated at about 500–600 mm, with rainfall mostly in the autumn-winter seasons. Mean January temperature is 2–3 °C and, in July, it is 22 °C. The dry summer period lasts from July to September. Winds blow mostly from the southeast and rarely from the northeast. Mean annual precipitation over the mountain areas of the coast (500 m a.s.l.) is about 600–1000 mm (Velev 2002). The western part of the coast is under the influence of the humid conditions of central Europe with precipitation more than 1000 mm/year.

Recent vegetation

The Bulgarian Black Sea coast covers a narrow strip of land located to the west of the Black Sea coastline. It is 375 km long and 30 to 50 km wide and includes Southern Dobrudzha, the Eastern Stara Planina Mountains (Balkan Range), Burgas Plain and the Eastern Strandzha Mountains. Climate controls and local topography play a dominant role in determining the pattern of highly-varied natural vegetation. This area is considered as a major pollen source area for the investigated core sediments with consideration of wind pattern, river input and gyre systems in the Black Sea. In addition to the vegetation distribution map, simplified characteristics of vegetation types are presented by Bondev (1991). According to this author, the study area falls within the Black Sea region of the Euxinian province of the European deciduous forest. The vegetation is represented by steppe vegetation, different types of temperate deciduous forests, reed, psammophytic and halophytic vegetation. Steppe vegetation of natural origin dominated by *Stipa capillata* L., *Agropyron brandzae* Pantu et Solac., *Koeleria brevis* Stev., *Stipa lessingiana* Trin. et Rupr., *Artemisia lerchiana* Weber, *Adonis vernalis* L., *Adonis vogensis* Steven ex DC and *Paeonia tenuifolia* L., amongst others, is preserved only in the northern Bulgarian Black Sea coastal area, in the South Dobrudzha region (Cape Shabla and Cape Kaliakra areas). Xerothermic forest communities dominated by *Quercus cerris* L. and *Q. frainetto* Ten. are widespread in the eastern Balkan Range area (Eastern Stara Planina Mts.) (Cape Emine area). Restricted areas on northern slopes and lower moisture ravines are occupied by stands of southeuxinian taxa such as *Quercus polycarpa* Schur. and *Fagus orientalis* Lipsky along with *Carpinus betulus* L., *Acer campestre* L., *Q. cerris* and *Tilia tomentosa* Moench. Xeromesophytic communities comprised of *Q. polycarpa* and *Carpinus betulus* are spread in lowland sites and on hilltops, as well as in the Strandzha Mountains. Mediterranean elements, such as *Quercus pubescens* Willd., *Carpinus orientalis* Mill., *Fraxinus ornus* L., *Phillyrea latifolia* L., *Celtis australis* L. and *Colutea arborescens* L. are distributed along the southern Black Sea coast. Relic southeuxinian forests of *Fagus orientalis*, with an undergrowth of evergreen shrubs (*Rhododendron ponticum* L., *Ilex aquifolium* L. and *Daphne pontica* L.) cluster the more humid ravines of the Strandzha Mts. (Veleka River, Rezovska River and Sozopol area). Riparian forests (so called Longoz) line rivers flowing into the Black Sea and coastal lakes. The main components of these forests are *Fraxinus oxycarpa* Willd., *Ulmus minor* Mill., *Carpinus betulus*, *Quercus pedunculiflora* C. Koch and *Alnus glutinosa* (L.) Gaerth. The most characteristic for these periodically flooded forests is the presence of lianas such as: *Hedera helix* L., *Periploca graeca* L., *Clematis vitalba* L., *Vitis vinifera* L. and *Smilax excelsa* L. Reed vegetation represented by communities dominated by *Phragmites australis* (Cav.) Trin. ex Steud., *Typha angustifolia* L., *T. latifolia* L. and *Schoenoplectus lacustris* (L.) Palla are spread along the rivers and the periphery of coastal lakes (Kochev and Jordanov 1981). Psammophytic vegetation includes communities mainly of *Leymus racemosus* (Lam.) Tzvel. ssp. *sabulosus* (Bieb.) Tzvel., *Ammophilla arenaria* (L.) Link, *Centaurea arenaria* Bieb. ex Willd., *Galilea mucronata* (L.) Parl and shrub communities with *Cionura erecta* (L.) Grsb. growing on the sandy beaches and dunes. Halophytic vegetation presented by communities of *Salicornia europaea* has limited distribution in habitats with high salinity.

Material and methods

Coring and sampling

Sediments pertinent to this study were collected during expeditions in 2009 and 2011 onboard the Research Vessel *Akademik* owned by the Institute of Oceanology of the Bulgarian Academy of Sciences. The two cruise expeditions recovered a series of sediment cores on a number of shallow-to-deep transects from the Bulgarian Black Sea area. The Varna transect consists of three cores taken from the shelf, continental slope and deep-water zone of the Black Sea (Fig. 1). Sediment core Akad 09-10 was collected with a Vibracore device, because of the feature of the Black Sea consolidated shelf sediments and cores Akad 09-15 and Akad 11-17 were collected with Gravity Corer device. The both devices have the same dimensions of the diameter of a metal tube and a length of metal tube, respectively Ø12 cm and 4 m. The recovered sediment cores were cut in 1-m sections on board and carried to the lab. The sediment was pulled from the steel tube in its plastic steeve, split lengthwise in two half cylinders, photographed, visually lithologically described and sampled. Samples of 1 cm³ were removed from the centre of the split section to avoid contamination with any younger sediment smeared downwards during the insertion of the sediment into the plastic steeve. The cores were lithologically described (Fig. 2) and sampled at every 10 cm on the board of the Research Vessel “Akademik” for further analyses.

Core Akad 11-17 (42°51'13.50"N, 29°01'08.50"E) was recovered from a water depth of 1805 m in the Black Sea deep-water zone (Fig. 1). The investigated length of the core is 229 cm (Fig. 2). From the core base up to the depth of 59 cm, the core sediments are typical lacustrine clay sediments with alternately light and dark layers, deposited under freshwater to brackish conditions (Unit III). From 229 to 133 cm, red-brown clay with grey clay is deposited in several pulses. These red-brown clay layers can be found in the sediments from the whole western Black Sea Basin. In the interval 155–153 cm were described six sand silt lamination layers. Above the red-brown clay was described an alternation of light grey clay with dark grey clay with a band of sulphides. At 69, 72, 72.5, 76, 80, 84, 90, 109–110 cm was described 1 mm thin sand silt lamination. The marine units II and I contain organic-rich microlaminated sapropel sediments and carbonate-rich finely laminated coccolith ooze and are ascertained in the core intervals from 59–27 cm and 27–0 cm to the top, respectively (Fig. 2). The base of the sapropel deposition in the core Akad 11-17 was described at 59 cm. The base of the coccolith ooze was described at 27 cm.

Core Akad 09-10 (42°54.8'N, 28°45.6'E) was recovered from a water depth of 1000 m on the Bulgarian Black Sea continental slope (Fig. 1). The investigated length of the core is 242 cm (Fig. 2). From 242 to 122 cm, sediments are typically lacustrine (Unit III) with homogeneous light to dark grey clay deposited under freshwater to brackish conditions. An important lithological feature of Unit III is the deposition of red-brown clay layers within the range from 236 to 216 cm. The onset of marine sapropel sediment deposition is lithologically determined at 126 cm (Unit II). The sapropel mud is finely laminated, more firm, dark green-grey with three white laminae in the interval from 122 to 123 cm in the lower part of marine Unit II. The boundary between Unit II and Unit I is delimited by the presence of coccolith ooze as well as the stable appearance of *Emiliania huxleyi* at 50 cm.

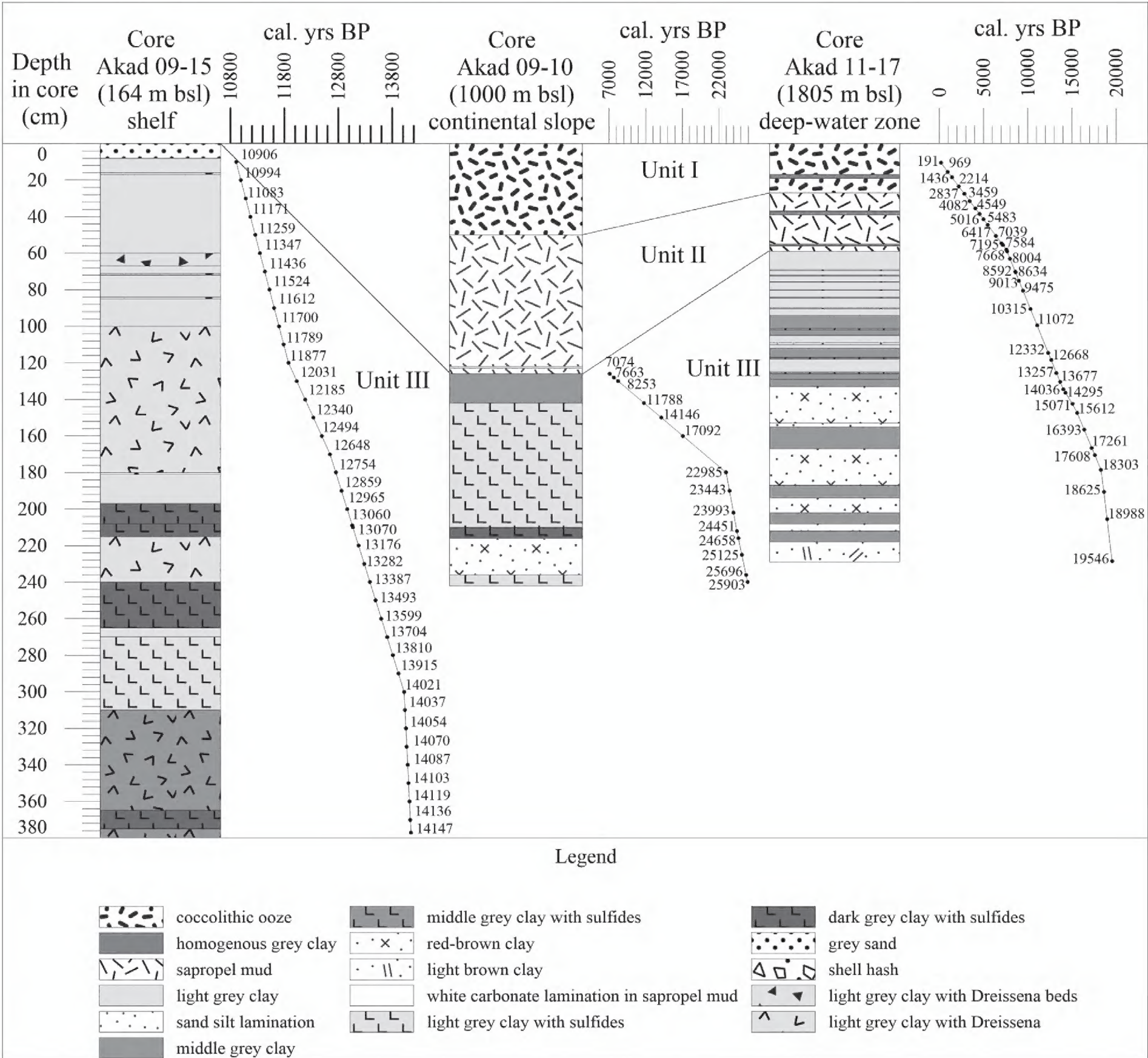


Figure 2. Lithological and geochronological correlations of the studied cores AKAD 11-17, AKAD 09-10 and AKAD 09-15.

Core Akad 09-15 (42°58.628'N, 28°33.147'E) was recovered from a water depth of 164 m on the Bulgarian Black Sea shelf (Fig. 1). The investigated length of the core is 380 cm. In this core, only lacustrine sediments (Unit III, lutite) were established (Fig. 2). From 380 to 8 cm, sediments are light to dark grey clay with rare whole disarticulated small freshwater *Dreissena* sp. and more fragmented shells. At 180 cm is described a layer of shell hash. In the interval from 8 to 0 cm, sediments are of grey sand.

Pollen analysis and zonation

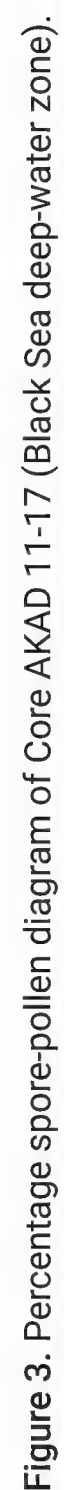
A total of 105 samples were selected for palynological, dinoflagellate cyst and other non-pollen palynomorph analyses. Each sample consists of 1 cm³ of wet sediment. The sampling interval was 10 cm. Sediments characterised by much higher sedimentation rates were sampled with varying resolution (Figs 2–8). All samples were processed according to the standard procedure of Faegri and

Iversen (1989). The laboratory technique includes treatment with hot 10% hydrochloric acid (HCl), cold 40% hydrofluoric acid (HF), solution of zinc chloride (ZnCl_2), 10% potassium hydroxide (KOH), glacial acetic acid (CH_3COOH), 2 min acetolysis and glacial CH_3COOH and ethanol ($\text{C}_2\text{H}_5\text{OH}$). The removal of mineral components was performed using sodium pyrophosphate and hydrofluoric acid (Birks and Birks 1980). The obtained suspension is stored in glycerine and then used for microscope analysis. A minimum of 500 up to 1000 identifiable pollen grains from terrestrial plants and a minimum of 100 up to 300 dinoflagellate cysts and non-pollen palynomorphs were counted in each sample to ensure statistical significance.

Pollen types were identified using the reference collection of modern pollen types of the Museum of Natural History of Varna, keys in Erdtman et al. (1961), Beug (1961, 2004), Moore and Webb (1978), Faegri and Iversen (1989) and photographs of Reille (1992, 1995). Dinoflagellate cysts taxonomy is based on Wall et al. (1973) and Marret et al. (2004). Other non-pollen palynomorphs (NPPs) were identified by the keys in van Geel et al. (1981), van Geel (2001) and Jankovska and Komarek (2000). The total pollen sum (PS) used for percentage calculations of the individual percentages includes arboreal pollen (AP) and non-arboreal pollen (NAP). Pollen of aquatics, spores, dinoflagellate cysts and other NPPs are excluded from the PS. Their presence was expressed as percentage of the total PS (van Geel et al. 1981). The software TILIA v.1.17.16 (Grimm 2011) was used for pollen and dinocyst percentage calculations and construction of spore-pollen and dinocyst diagrams. A 10× exaggeration of the horizontal scale was used to show changes of low-percentage taxa. The spore-pollen diagrams were subdivided into fifteen local pollen assemblage zones (LPAZ) (Figs 3, 5, 7) and two local dinoflagellate assemblage zones (LDAZ) (Figs 4, 6, 8) using visual inspection of the main changes in taxa composition (described in details in Table 2). The cluster analysis programme CONISS (Grimm 1987) is applied for more precise zonation (Figs 3, 5, 7). These LPAZ are correlated with the established regional pollen assemblage zones (RPAZ) IV to IX after Filipova-Marinova (2006a) (Table 3). In the spore-pollen diagrams, taxa are ordered by their plant functional type (Prentice et al. 1996).

Correlations and interpretation of data from spore-pollen analysis

The stratigraphic subdivision of sediments from the western Black Sea area is based on qualitative interpretation of the pollen and spore assemblages and the vertical and spatial distribution of selected indicator taxa. The pollen assemblage zones distinguished are based entirely on the percentage abundances of the predominant and indicator pollen and spores in the assemblages. Pollen spectra delimited for each assemblage zone were obtained from several samples in each sediment core and provide a picture of vegetation changes for the period represented by sediments. According to Birks (1973), the assemblage zones for an individual core have to be considered as local pollen assemblage zones (LPAZ). As these zones are present in two to several sediment cores in adjacent areas, they are further delimited as regional pollen assemblage zones (RPAZ). These RPAZ can be proposed as a regional biostratigraphy and they can be correlated in time and space with concurrent chronostratigraphic scales (Berglund 1983). These LPAZ and RPAZ (Table 3) are tentatively correlated to



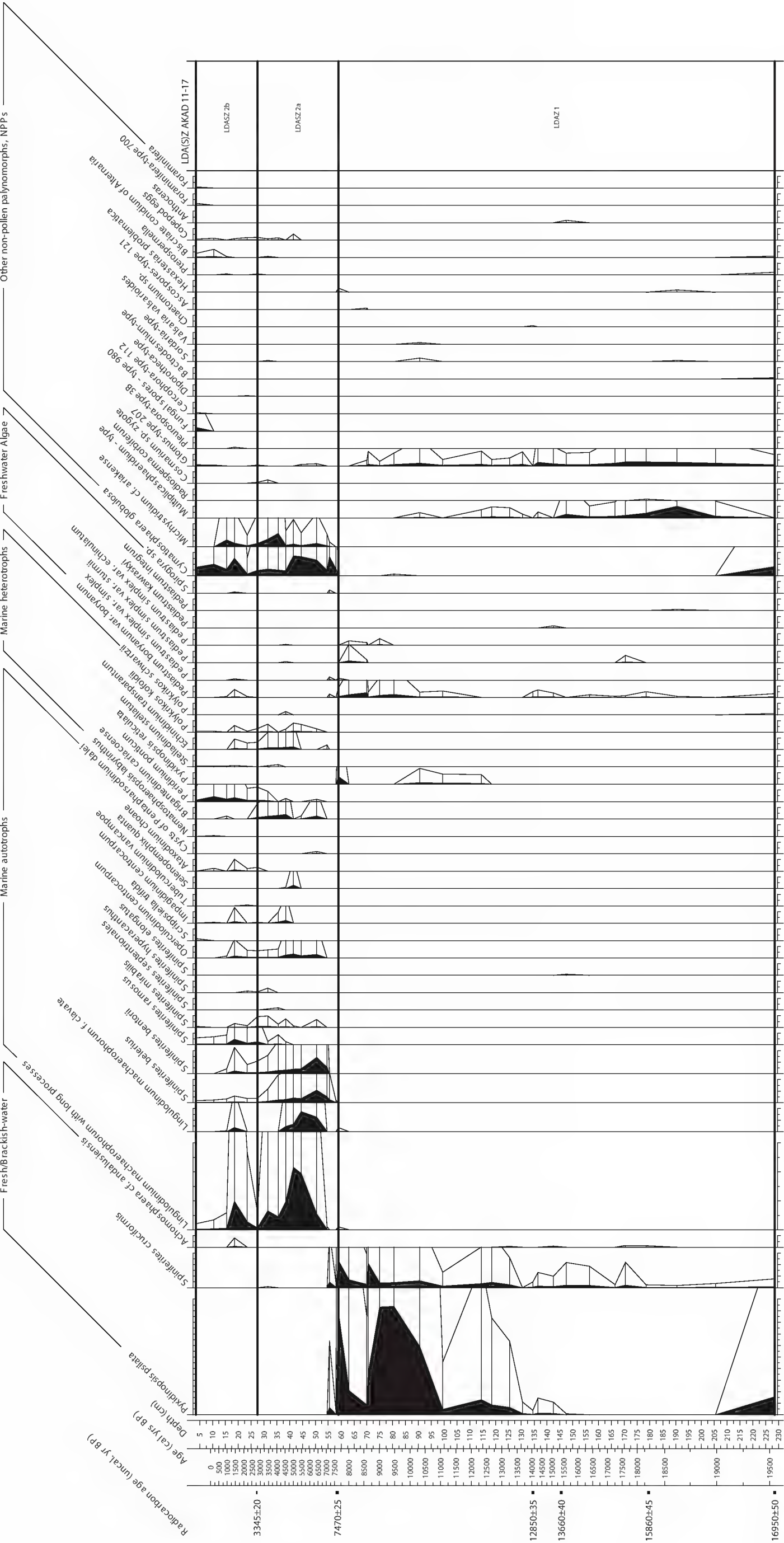
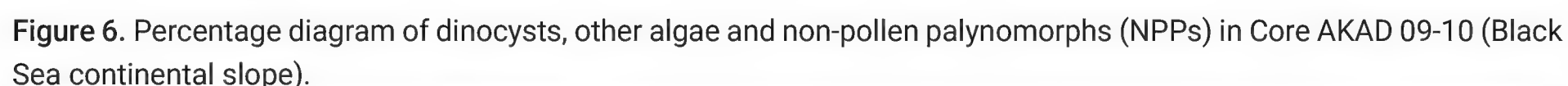


Figure 4. Percentage diagram of dinocysts, other algae and non-pollen palynomorphs (NPPs) in Core AKAD 11-17 (Black Sea deep-water zone).



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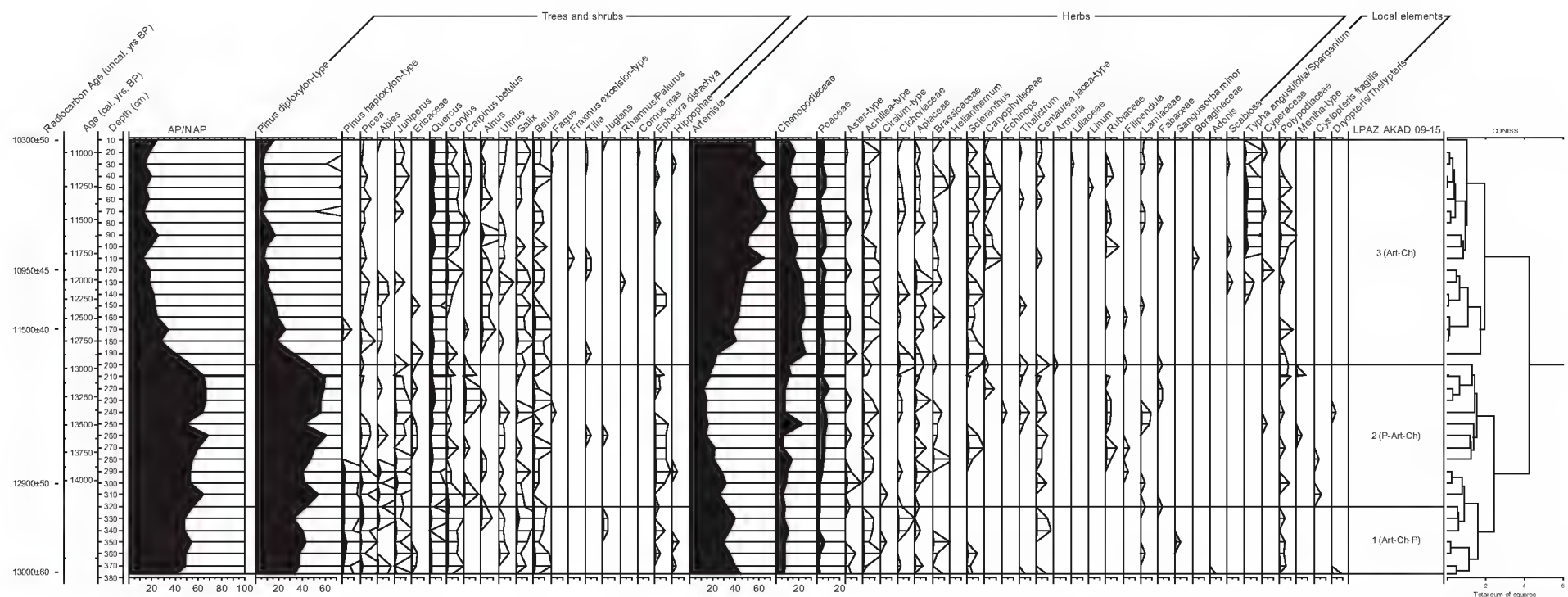


Figure 7. Percentage spore-pollen diagram of Core AKAD 09-15 (Black Sea shelf).

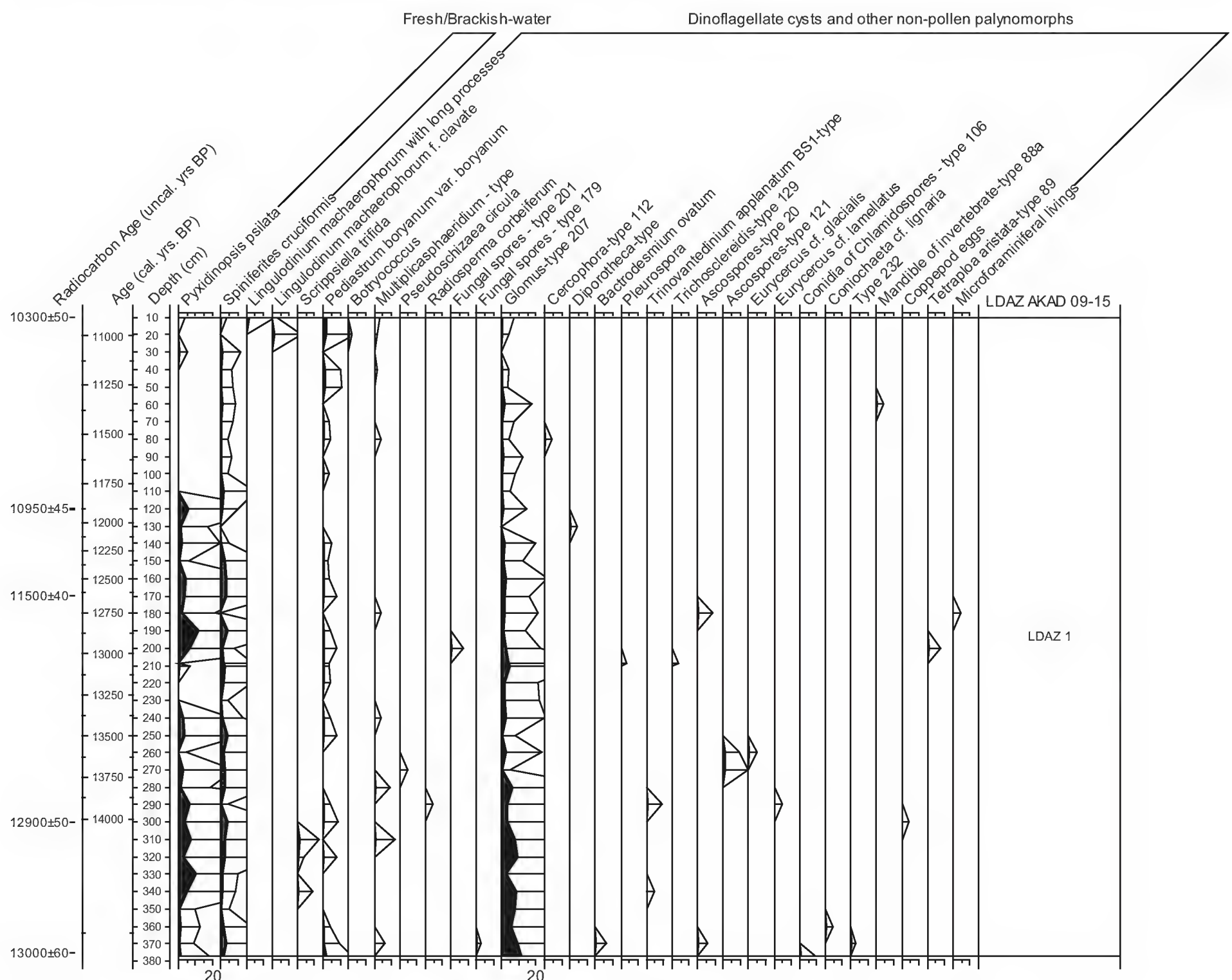


Figure 8. Percentage diagram of dinocysts, other algae and non-pollen palynomorphs (NPPs) in Core AKAD 09-15 (Black Sea shelf).

lished for all three cores (Fig. 2). Nine sediment samples from Core Akad 09-10 and Akad 09-15 were selected for ^{14}C AMS dating of bulk organic carbon at the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) Facility,

Table 1. Chronology of the studied cores AKAD 11-17, AKAD 09-10 and AKAD 09-15.

Core AKAD	Depth (cm)	Lab. No	Material dated	Uncalibrated yrs BP	Calibrated yrs BC (2σ range)	Calendar yrs BP*
11-17	27	GdA-2598	Bulk	3345±20	909–732	2759
11-17	58.5	GdA-2599	Bulk	7470±25	5722–5537	7584
11-17	134.5	GdA-2601	Bulk	12850±35	12170–11866	13971
11-17	145.5	GdA-2602	Bulk	13660±40	13687–13233	15395
11-17	179.5	GdA-2603	Bulk	15860±45	16587–16175	18346
11-17	228.5	GdA-2604	Bulk	16950±50	17798–17343	19534
09-10	126	OS-79014	Bulk	6920±40	5271–4978	7074
09-10	180	OS-79016	Bulk	19850±170	21500–20592	22985
09-10	212	OS-79017	Bulk	21100±170	23073–22054	24451
09-10	240	OS-79018	Bulk	22400±230	24444–23510	25903
09-15	10	OS-79753	Mollusk	10300±50	9151–8757	10906
09-15	120	OS-79754	Mollusk	10950±45	10181–9582	11877
09-15	170	OS-90808	Mollusk	11500±40	10807–10603	12648
09-15	300	OS-79756	Mollusk	12900±50	12234–11892	14021
09-15	375	OS-74855	Mollusk	13000±60	12562–11954	14144

* detrital carbon correction (reservoir effect) of 363 ± 41 years is applied.

WHOI, USA. Six more sediment samples from Core Akad 11-17 were selected for ¹⁴C dating at the Gliwice Radiocarbon Laboratory of the Silesian Institute of Technology, Poland. An “Age vs. Depth” model (Fig. 2) was developed for all three cores by 2σ-range calibration of the available radiocarbon dates (Table 1, Fig. 2) with the online calibration programme CALIB 7.1. (Stuiver et al. 2017), using the MARINE13 curve (Reimer et al. 2013) with application of a Reservoir effect (ΔR) of 363 ± 41 yrs (Siani et al. 2000) in order to correlate the obtained results with the available geochronological and archaeological data. The sedimentation rate for this model was calculated by Tilia software (Grimm 2011). This method allows each pollen sample as well as the LPAZ boundaries to be assigned to the relevant calendar age in years BP. All the dates in the pollen diagrams and the text are given as calendar years BP (cal. yrs BP).

Results

On the pollen diagrams, six LPAZ from Core AKAD 11-17 (LPAZ AKAD 11-17 1–6) and four LPASZ (LPASZ AKAD 11-17 2 a, b, c, d) (Fig. 3); Six LPAZ from Core AKAD 09-10 (LPAZ AKAD 09-10 1–6) (Fig. 5); Three LPAZ from Core AKAD 09-15 (LPAZ AKAD 09-15 1–3) (Fig. 7) were recognised. They reflect successive changes in vegetation development in the study area. Two local dinoflagellate cyst (dinocyst) assemblage zones (LDAZ 1 and 2) were distinguished (Figs 4, 6, 8). The second dinocyst zone is subdivided into two subzones (LDASZ-2a and LDAZ-2b). All zones are described in detail in Table 2.

Discussion

Pollen assemblages

Regional Pollen Assemblage Zone IV (*Artemisia* – *Chenopodiaceae* – *Pinus*)
25903–15612 cal. yrs BP

RPAZ IV has a Late Pleniglacial-Oldest Dryas/Upper Neoeuxinian age (25903–15612 cal. yrs BP). It is represented in cores AKAD 09-10 (LPAZ AKAD 09-10 1 and 2) (Fig. 5, Tables 2, 3) and AKAD 11-17 (LPAZ AKAD 11-17 1) (Fig. 3, Tables 2, 3). Sediments with Late Pleniglacial and Oldest Dryas age cannot be separated by pollen analysis in cores studied, because of the similarity in pollen spectra.

Table 2. Description of the local pollen assemblage zones and subzones (LPA(S)Z) and local dinoflagellate cyst assemblage zones and subzones (LDA(S)Z) from cores AKAD 11-17, AKAD 09-10 and AKAD 09-15.

LPAZ AKAD11-17-1 (228.5–147.5 cm) 19546-15612 cal. yrs BP Artemisia-Chenopodiaceae-Pinus Dominant non-arboreal pollen (NAP) (up to 72%), mainly <i>Artemisia</i> (around 50%) and <i>Chenopodiaceae</i> (10%). Continuous <i>Poaceae</i> (ca. 2%), <i>Aster</i>-t. (1%) and <i>Brassicaceae</i> (1%). Sporadic <i>Achillea</i>-t., <i>Caryophyllaceae</i> and <i>Scleranthus</i>. Arboreal pollen (AP) dominated by <i>Pinus diploxylon</i>-t. (up to 25%). Regular presence with low values (up to 1%) of <i>Picea</i>, <i>Abies</i>, <i>Juniperus</i> and <i>Ephedra distachya</i>. Gradual decrease of <i>Quercus</i> from 12% up to 3% and of <i>Corylus</i> (3.8-0.5%) at zone top. Continuous low <i>Betula</i> and <i>Ulmus</i> (up to 0.8%). Sporadic <i>Alnus</i>, <i>Carpinus betulus</i>, <i>Fagus</i> and <i>Tilia</i>.	LPASZ AKAD11-17-2a (147.5–136.5 cm) 15612-14295 cal. yrs BP Pinus-Artemisia-Chenopodiaceae Maximum of <i>Pinus diploxylon</i>-t. (up to 42%), coincident with decrease of <i>Artemisia</i> (50 to 35%), constant <i>Chenopodiaceae</i> (to 12.8%). Constant presence of <i>Quercus</i> (ca. 4%), <i>Corylus</i>, <i>Ulmus</i> and <i>Salix</i> (ca. 1%). Sporadic <i>Hippophae</i>. <i>Poaceae</i>, <i>Cichoriaceae</i>, <i>Aster</i>-t., <i>Achillea</i>-t., <i>Brassicaceae</i> and <i>Centaurea jacea</i>-t. are continuously presented.	LPASZ AKAD11-17-2b (136.5–134.5 cm) 14295-14036 cal. yrs BP Artemisia-Chenopodiaceae One spectrum: Rapid rise of <i>Artemisia</i> (35-70%) and <i>Chenopodiaceae</i> (up to 16%). Presence of <i>Poaceae</i> (2%) and <i>Achillea</i>-t. (2%). Rapid decrease in <i>Pinus diploxylon</i>-t. (from 42% to 6%). Slight increase in <i>Juniperus</i> and <i>Ephedra distachya</i>. Decline of <i>Quercus</i> (from 4% to 1.5%).
LPASZ AKAD11-17-2c (134.5–125.5 cm) 14036-13257 cal. yrs BP Pinus-Artemisia Two spectra: Rapid rise of <i>Pinus diploxylon</i>-t. (from 6% to 25%), decrease of <i>Artemisia</i> (from 70% to 58%) and <i>Chenopodiaceae</i> (from 15% to 10%). Continuous <i>Poaceae</i> (around 2%). Presence of <i>Picea</i>, <i>Quercus</i>, <i>Corylus</i>, <i>Juniperus</i> and <i>Ephedra distachya</i>.	LPASZ AKAD11-17-2d (125.5–99.5 cm) 13257-11072 cal. yrs BP Artemisia-Chenopodiaceae Sharp rise of NAP (up to 86%), including highest values of <i>Artemisia</i> (around 67%), max. at the zone bottom. (up to 82%). Gradual increase of <i>Chenopodiaceae</i> (11-16%) and <i>Poaceae</i> (1-3%) at the zone top. <i>Pinus diploxylon</i>-t. after sharp decrease is stabilised below 11%. Constant <i>Quercus</i> (around 2-3%), increased <i>Corylus</i> (up to 1%) at the zone top. Regular low presence of <i>Picea</i>, <i>Juniperus</i>, <i>Ericaceae</i>, <i>Ephedra distachya</i>, <i>Betula</i>, <i>Salix</i> and <i>Hippophae</i>. Presence of numerous heliophytes including <i>Helianthemum</i>, <i>Scleranthus</i>, <i>Caryophyllaceae</i>, <i>Centaurea jacea</i>-t.	LPASZ AKAD11-17-3 (99.5–63 cm) 11072-8004 cal. yrs BP Quercus-Artemisia-Chenopodiaceae Gradual rise of <i>Quercus</i> (1-16%), coincidently with decrease of <i>Artemisia</i> (from 64% to 34%). Abrupt decrease in <i>Pinus diploxylon</i>-t. (up to 5%) at the zone top. Trend to rise of <i>Picea</i>, <i>Betula</i>, <i>Corylus</i> and <i>Salix</i> (up to 2%) at the zone top. First significant presence of <i>Carpinus betulus</i> (6%). Presence of <i>Ephedra distachya</i> (0.8%) and <i>Hippophae</i> (0.2%). <i>Typha angustifolia/Sparganium</i>-t., <i>Athyrium</i> and <i>Dryopteris/Thelypteris</i>-t. appear.
LPAZ AKAD11-17-4 (63–44.5 cm) 8004-5483 cal. yrs BP Quercus-Corylus-Carpinus betulus-Ulmus-Cerealia-Triticum Dominant <i>Quercus</i> (max. 29%) and <i>Corylus</i> (max. 27%). Consistent increase in <i>Ulmus</i> (0.5-7 %) and <i>Tilia</i> (up to 1.2%). Abundance of <i>Salix</i> and frequent <i>Betula</i> (about 1.1%). Rise of <i>Alnus</i> (up to 3.1%) and <i>Fagus</i> (up to 5.4%) at the zone top. Sporadic <i>Fraxinus excelsior</i>-t., <i>Acer</i>, <i>Pistacia</i> and <i>Hippophae</i>. Constant presence of <i>Hedera</i>. <i>Carpinus orientalis</i> and <i>Fraxinus ornus</i> appear. Decrease in <i>Pinus haploxylon</i>-t. (from 20% to 2.4%). Increase in <i>Picea</i> (up to 1.1%). <i>Abies</i>, <i>Juniperus</i> and <i>Ericaceae</i> are sporadic. Decrease in <i>Artemisia</i> (from 64.4 to 13%) and <i>Poaceae</i> (from 8.5 to 2.6%). Decline of <i>Chenopodiaceae</i> (from max. 24.9% to 2.4%). Appearance of <i>Cerealia</i>-t. (1.3%) and <i>Triticum</i>. <i>Achillea</i>-t., <i>Aster</i>-t., <i>Cichoriaceae</i>, <i>Brassicaceae</i>, <i>Scleranthus</i>, <i>Plantago lanceolata</i>, <i>Polygonum aviculare</i>, <i>Caryophyllaceae</i> and <i>Centaurea jacea</i>-t. present. <i>Polypodiaceae</i> (around 0.8%), <i>Typha angustifolia/Sparganium</i>-t., <i>Typha latifolia</i> and <i>Cyperaceae</i> are continuously present.	LPAZ AKAD11-17-5 (44.5–27.5 cm) 5483-2837 cal. yrs BP Quercus-Carpinus betulus-Corylus-Fagus-Carpinus orientalis-Cerealia Dominant <i>Quercus</i> (about 28.4%). Gradual rise and maximal presence of <i>Carpinus betulus</i> (12.2-18.4%). Decrease in <i>Corylus</i> within the zone (16.8 to 8.1%). Constant presence of <i>Alnus</i> (around 6.1%), <i>Tilia</i> (1.8%), <i>Carpinus orientalis</i> (0.7%), <i>Fagus</i> (6%), <i>Betula</i> (0.1%), <i>Pinus diploxylon</i>-t. (9.5%). Decrease in <i>Ulmus</i> (6-2.3%) at the zone top. Rise of <i>Ericaceae</i> (up to 0.9%). Sporadic <i>Salix</i>, <i>Acer</i> and <i>Ephedra distachya</i>. Continuous <i>Hedera</i>; <i>Humulus/Cannabis</i> appear. Reduced <i>Artemisia</i> (34% to 8%), <i>Chenopodiaceae</i> (21% to 3.6%) and <i>Poaceae</i> (6.6% to 3.6%). <i>Cerealia</i>-t. and <i>Triticum</i> are continuously presented (around 0.6%). Presence of <i>Aster</i>-t., <i>Achillea</i>-t., <i>Cichoriaceae</i>, <i>Carduus</i>-t., <i>Plantago lanceolata</i>, <i>Polygonum aviculare</i>, <i>Scleranthus</i>, <i>Filipendula</i> and <i>Apiaceae</i>. <i>Polypodiaceae</i>, <i>Cyperaceae</i>, <i>Typha angustifolia/Sparganium</i>-t., <i>Myriophyllum spicatum</i> and <i>Alisma</i> are sporadic.	LPAZ AKAD11-17-6 (27.5–3.5 cm) 2837 cal. yrs BP-preindustrial time Quercus-Alnus-Ulmus-Carpinus betulus-Fagus Gradual rise of AP (69 to 84%). Dominant <i>Quercus</i> (around 20%). Rise of <i>Alnus</i> (max. 20%) at the zone top. Continuous <i>Ulmus</i> (around 3.7%) and <i>Fagus</i> (around 5%). Increase in <i>Carpinus betulus</i> (up to 8%) and <i>Corylus</i> (up to 7%). Constant <i>Carpinus orientalis</i> and <i>Tilia</i> (around 1%). Constant <i>Hedera</i> (0.3%). <i>Vitis</i> and <i>Humulus/Cannabis</i> appear. Reduced <i>Artemisia</i> (to 8.4%) at the zone top. <i>Chenopodiaceae</i> and <i>Poaceae</i> are low (2-3%). Continuous <i>Cerealia</i>-t. (1%) and <i>Triticum</i> (0.2%). <i>Plantago lanceolata</i>, <i>Polygonum aviculare</i>, <i>Centaurea cyanus</i> and <i>Rumex</i> are also presented.

LDZ AKAD11-17-1 (228.5–59 cm) 19546-7668 cal. yrs BP <i>Pyxidínopsis psilata-Spiniferites cruciformis</i> Dominant dynoflagellate cysts of <i>Pyxidínopsis psilata</i> (two max. 93.7 and 80.5%), then disappearing. Continuous <i>Spiniferites cruciformis</i> (two max. 20.9% and 23.2% at the zone top), then disappearing. Rise of <i>Pediastrum boryanum</i> var. <i>boryanum</i> (up to 5.1%), <i>Pediastrum simplex</i> var. <i>simplex</i> (around 3.7%), <i>Pediastrum simplex</i> var. <i>sturmii</i> and <i>Pyxidínopsis reticulata</i> are also presented. Other NPPs such as acritarchs <i>Cymatiosphaera globulosa</i> and <i>Hexasteria problematica</i> and fungal spores of <i>Bactrodesmium</i>-type, <i>Sordaria</i>-type, <i>Valsaria valsaroides</i>, <i>Ascospore</i>-type, Biscariate conidium of <i>Alternaria</i> and animal remains of <i>Anthoceras</i> are sporadic.	LDZ AKAD11-17-2a (59–27.5 cm) 7668-2837 cal. yrs. BP <i>Lingulodinium machaerophorum-Spiniferites belerius-Spiniferites bentorii</i> Increase of <i>Spiniferites bentorii</i> (max. 14%) and <i>S. belerius</i> (max. 10.5%) at the zone bottom, followed by rapid increase in <i>Lingulodinium machaerophorum</i> with long processes (max. 107.7%). Substantial presence of <i>S. ramosus</i>, <i>S. mirabilis</i> and <i>S. hyperacanthus</i>. <i>Operculodinium centrocarpum</i> (3.4%), <i>Brigantedinium cariacense</i> (3.8%), <i>Impagidinium centrocarpum</i> (1.4%) and <i>Echinidinium transparentum</i> (1.5%) appear at the zone bottom and then decrease to 0.1%. <i>Peridinium ponticum</i>, <i>Spiniferites mirabilis</i>, <i>Protoperidinium stellatum</i> and <i>Spiniferites hyperacanthus</i> are sporadic. Increase in acritarchs <i>Cymatiosphaera globulosa</i> (up to 17.2%), then decreasing. First appearance of <i>Michrystidium</i> cf. <i>ariakense</i> (max. 11.5%), <i>Polykrikos kofoidii</i> (0.6%) and Copepod eggs (0.5%). Sporadic <i>Polykrikos schwartzii</i>, <i>Pleurospora</i>-t.3B, <i>Spirogyra</i> sp. and <i>Selenopemphix quanta</i>. Other NPPs such as Biscariate conidium of <i>Alternaria</i>, <i>Pentaphrasodinium dalei</i> and <i>Glomus</i>-type are rare	LDZ AKAD11-17-2b (27.5–3.5 cm) 2837 cal. yrs. BP – present <i>Lingulodinium machaerophorum-Spiniferites ramosus</i> Decrease of <i>Lingulodinium machaerophorum</i> (48.9% to 1.7%), <i>Spiniferites bentorii</i> (to 0.4%) and <i>S. belerius</i> (to 0.2%). Increase in <i>S. ramosus</i> (up to 4.7%) and <i>Peridinium ponticum</i> (to 4.5%). Sporadic presence of <i>Ataxodinium choane</i>, <i>Achomosphaera</i> cf. <i>andalousiense</i>, Fungal spores-type 980, Biscariate conidium of <i>Alternaria</i>, <i>Pediastrum boryanum</i> var. <i>boryanum</i>, <i>Pediastrum simplex</i> var. <i>sturmii</i>. Constant values of acritarchs <i>Cymatiosphaera globulosa</i> (15-5.7%). Presence of <i>Michrystidium</i> cf. <i>ariakense</i> (max. 5.9%)
LPAZ AKAD09-10-1 (240–160 cm) 25903-17092 cal. yrs BP <i>Artemisia-Chenopodiaceae-Pinus</i> Dominant <i>Artemisia</i> (28-49%), constant Chenopodiaceae (6-16%), high <i>Pinus diploxylon</i>-t. (max. 33%). Sporadic <i>Picea</i> and <i>Abies</i>. Maximum of <i>Juniperus</i> (5-10%). Low <i>Quercus</i> (2.7%) and <i>Corylus</i> (1.6-4.3%). Sporadic Ericaceae, <i>Betula</i>, <i>Carpinus betulus</i>, <i>Salix</i>, <i>Ulmus</i> and <i>Alnus</i>. Continuous Polypodiaceae (2%). Many Late-Glacial heliophytes are presented.	LPAZ AKAD09-10-2 (160–142 cm) 17092-11788 cal. yrs BP <i>Pinus-Artemisia-Chenopodiaceae</i> Dominant <i>Pinus diploxylon</i>-t., decreasing <i>Juniperus</i> (from 7.1% to 1.7%). Appearance of <i>Pinus haploxylon</i>-t. and <i>Ephedra distachya</i>. Decrease in <i>Artemisia</i> (from 42% to 24.2%) and Poaceae (from 7.1% to 3.8%). Constant Chenopodiaceae (around 10%). Rise of <i>Quercus</i> (from 4.3% to 19.8%), constant <i>Corylus</i> (around 2%).	LPAZ AKAD09-10-3 (142–130 cm) 11788-8253 cal. yrs BP <i>Quercus-Artemisia-Corylus</i> Two spectra: <i>Pinus diploxylon</i>-t. strongly reduced to ca. 8% at the zone top. High <i>Quercus</i> (max. 32.5%), increased <i>Corylus</i> (from 5.5% to 15%), <i>Ulmus</i> (up to 4%) and <i>Fagus</i> (to 1.6%). Frequent <i>Carpinus betulus</i> and <i>Betula</i>. Sporadic <i>Humulus/Cannabis</i> and <i>Ephedra distachya</i>. Decreased <i>Artemisia</i> (up to 17.3%), Chenopodiaceae (up to 4.8%) and Poaceae (up to 2.5%).
LPAZ AKAD09-10-4 (130–100 cm) 8253-ca.5500 cal. yrs BP <i>Quercus-Corylus-Carpinus betulus-Ulmus-Cerealia-Triticum</i> Dominant <i>Quercus</i> (around 30%), <i>Corylus</i> at max. (28.3%) in the middle of the zone. Increase of <i>Carpinus betulus</i> (from 1.2% to 16.3%), <i>Fagus</i> (from 0.9% to 7.1%) and <i>Alnus</i> (from 1.2% to 4.6%) at the zone top. Continuous <i>Ulmus</i> (around 7%), <i>Fraxinus excelsior</i>-t. (2.8%) ant <i>Tilia</i> (1.9%). Constant <i>Hedera</i> (ca. 0.5%). Appearance of <i>Cornus mas</i> and <i>Acer</i>. <i>Ephedra distachya</i> disappear. Reduced <i>Artemisia</i> (from 24% to 0.6%), Chenopodiaceae (from 3.8% to 0.7%) and Poaceae (from 2.5% to 1.4%). Substantial <i>Cerealia</i>-t. (0.8%) and <i>Triticum</i> (0.8%). Frequent <i>Aster</i>-t. and <i>Achillea</i>-t. (up to 1%). Appearance of <i>Plantago lanceolata</i> and <i>Urtica</i>. Sporadic <i>Filipendula</i> and <i>Scleranthus</i>.	LPAZ AKAD09-10-5 (100–36 cm) ca.5500-ca.2800 cal. yrs BP <i>Quercus -Carpinus betulus-Fagus-Corylus-Carpinus orientalis-Cerealia</i> Dominant <i>Quercus</i> (from 20% to 28%), <i>Carpinus betulus</i> at max. (17.5%), followed by a decrease to 1.5%. Maximum of <i>Fagus</i> (7.5%), followed by decrease to 2.8%. Decline of <i>Corylus</i> (from 20% to 5.8%) and <i>Ulmus</i> (from 3.7% to 1.6%). First appearance of <i>Carpinus orientalis</i> (1.3%). Continuous presence of <i>Pinus diploxylon</i>-t. (10%). Increase in <i>Artemisia</i> (from 6.5% to 24.6%). Chenopodiaceae and Poaceae are low (ca. 3-4%). Substantial <i>Cerealia</i>-t. (1%) and <i>Triticum</i> (1%). Presence of <i>Plantago lanceolata</i> (1.2%), <i>Polygonum aviculare</i>, <i>Centaurea jacea</i> and <i>Filipendula</i>.	LPAZ AKAD09-10-6 (36–10 cm) ca.2800 cal. yrs BP – present <i>Quercus-Alnus-Ulmus-Carpinus betulus-Fagus</i> Dominant <i>Quercus</i> (26%); increasing of <i>Alnus</i> (up to 10%) and <i>Ulmus</i> (up to 3%). Constant <i>Carpinus betulus</i> (17%), <i>Fagus</i> (3%), <i>Fraxinus excelsior</i> (1.6%) and <i>Hedera</i> (1.3%). Decrease in <i>Artemisia</i> (from 24.6% to 7.7%), Chenopodiaceae (from 5.5% to 1.1%). Increase in Poaceae (ca. 7.6%). Significant <i>Cerealia</i>-t. (1.6%) and <i>Triticum</i> (0.6%). Appearance of <i>Plantago lanceolata</i>, <i>Scleranthus</i> and <i>Carduus</i>-t.
LDZ AKAD09-10-1 (240–128 cm) 25903-7663 cal. yrs BP <i>Pyxidínopsis psilata-Spiniferites cruciformis</i> Dominant dinoflagellate cysts of <i>Pyxidínopsis psilata</i> (max. 28.2%) and <i>Spiniferites cruciformis</i> (1.4 to 10.7%). Constant presence of green algal species <i>Pediastrum boryanum</i> var. <i>boryanum</i> (2.2% to 3.4%), <i>Pediastrum simplex</i> var. <i>sturmii</i> (around 3.7%), <i>Botryococcus</i> sporadic. High <i>Glomus</i>-t.207 (1.5% to 6.3%). <i>Multiplicasphaeridium</i>-t., <i>Pleurospora</i>-t.3B, <i>Ascospores</i>-t.20, <i>Achomosphaera</i> cf. <i>andalousiense</i> and <i>Cymatiosphaera globulosa</i> are sporadic. First appearance of <i>Spiniferites ramosus</i> at the zone top. <i>Lingulodinium machaerophorum</i> appear sporadically at the zone top.	LDZ AKAD09-10-2a (128–40 cm) 7663-ca.2800 cal. yrs. BP <i>Lingulodinium machaerophorum-Spiniferites belerius-Spiniferites bentorii</i> Rapidly increasing dominant <i>Lingulodinium machaerophorum</i> with long processes (two max. 446% and 166%). <i>L. machaerophorum</i> f. <i>clavate</i> at max 28.7% at the zone bottom, followed by sharp decrease. <i>Spiniferites belerius</i> (max. 26.2%) and <i>S. bentorii</i> (max. 12.9%) form peaks at the zone bottom, then decreasing up to around 6%. High <i>Brigantedinium cariacense</i> (around 10%). Substantial <i>S. mirabilis</i>, <i>S. membranaceus</i> and <i>S. hyperacanthus</i>. Constant <i>Polykrikos kofoidii</i> (0.7-5%), <i>S. ramosus</i> (2.2%), <i>Operculodinium centrocarpum</i> (0.9-7.2%), <i>Echinidinium transparentum</i> (0.6-5.4%) and <i>Impagidinium aculeatum</i> (0.5-1.8%). Sporadic <i>Tectatodinium pellitum</i>, <i>Polykrikos schwartzii</i>, <i>Protoperidinium stellatum</i> and <i>Bitectatodinium tepikiense</i>. Rising of acritarch <i>Cymatiosphaera globulosa</i> (18.3%), <i>Michrystidium</i> cf. <i>ariakense</i> (max. 20%). <i>Pleurospora</i>-t.3B and Copepod eggs are also presented.	LDZ AKAD09-10-2b (40–10 cm) ca.2800 cal. yrs. BP – present <i>Lingulodinium machaerophorum-Peridinium ponticum</i> Dominant <i>Peridinium ponticum</i> (10%). Decrease in <i>Lingulodinium machaerophorum</i> (3.7%), <i>Spiniferites bentorii</i> and <i>S. belerius</i>. <i>Polykrikos schwartzii</i> increase (up to 2%). <i>Protoperidinium nudum</i> and <i>Operculodinium centrocarpum</i> are sporadic. Decrease in acritarchs <i>Cymatiosphaera globulosa</i> (1.8%). <i>Pleurospora</i> sp.-t.3B, Fungal spores-t.200, <i>Sordaria</i> and Copepod eggs are also presented.

LPAZ AKAD09-15-1 (377–320 cm) 14147-14054 cal. yrs BP Artemisia-Chenopodiaceae-Pinus Dominant <i>Artemisia</i> (max. 44%), constant Chenopodiaceae (11%), high <i>Pinus</i> diploxylon-t. (39-42%). Continuously low <i>Quercus</i> (2.7%), <i>Corylus</i> (1.5%), <i>Salix</i> (1%), <i>Betula</i> (1%), <i>Ulmus</i> (0.6%), <i>Juniperus</i> (2%), <i>Hippophae</i> (0.5%). Presence of <i>Ephedra distachya</i> (up to 0.8%). Continuous Poaceae (around 7%). Numerous Late-Glacial heliophytes are presented.	LPAZ AKAD09-15-2 (320–200 cm) 14054-12965 cal. yrs BP Pinus-Artemisia-Chenopodiaceae Dominant <i>Pinus</i> diploxylon-t. (max. 61%) decreasing <i>Artemisia</i> (from 31.5% to 12%); Chenopodiaceae peak in the middle of the zone (23.6%). Increase in Poaceae to 10%. Many Late-Glacial heliophytes are presented. Constant <i>Quercus</i> (4%), <i>Salix</i> (2%), <i>Betula</i> (2%), <i>Corylus</i> (1%).	LPAZ AKAD09-15-3 (200–10 cm) 12965-10906 cal. yrs BP Artemisia-Chenopodiaceae Dominant <i>Artemisia</i> (max. 67%) and Chenopodiaceae (24.6%); constant Poaceae (6-8%). Late-Glacial heliophytes are abundant. <i>Typha angustifolia/Sparganium</i> and Cyperaceae appear. Increase of Polypodiaceae (1-2%).
LDAZ AKAD09-15-1 (377–10 cm) 14147-10906 cal. yrs BP Pyxidinoopsis psilata-Spiniferites cruciformis Dominant dinoflagellate cysts of <i>Pyxidinoopsis psilata</i> (10%) and <i>Spiniferites cruciformis</i> (4%). Constant presence of green algal species <i>Pediastrum boryanum</i> var. <i>boryanum</i> (2%). Sporadic acritarchs of <i>Pseudoschizaea circula</i>. Constant presence of <i>Glomus</i>-type 207 (max. 11% at the zone bottom).		

Paleovegetation reconstruction, based on typical high values of non-arboreal taxa and the presence of cold-resistant and heliophilous taxa such as *Artemisia* and Chenopodiaceae, suggest spreading of cold and dry steppes. Different taxa of Poaceae were also important elements in the steppe communities along the coast together with other heliophilous taxa from Asteraceae, Cichoriaceae, Apiaceae, Brassicaceae, Caryophyllaceae and *Helianthemum*. According to Prentice et al. (1993), the growing season soil moisture deficit and low winter temperature would have maintained an open vegetation. However, climate aridity along the Bulgarian Black Sea coast was not so extreme because the presence of the desert shrub *Ephedra distachya*, that is an indicator of dry continental climate and an important constituent of the glacial flora, is constant but low. Patches of eurythermic conifers such as *Pinus* grow along the coast in valleys where favourable microclimatic conditions may have prevailed. The high percentage values of *Pinus diploxylon*-type pollen could also be an effect of long distance transport which became significantly more pronounced in an environment with sparse vegetation (Pardoe et al. 2010). Warming/humidity increase during the melting pulses (19.2 to 14.5 cal. ka BP) after the Last Glacial Maximum is expressed by the open coniferous forests development. The constant maximum presence of *Glomus* spores suggests significant erosion processes.

Temperate deciduous arboreal taxa such as *Quercus*, *Corylus*, *Ulmus*, *Betula* and *Alnus* show constant presence in the pollen diagrams. The presence of single pollen grains of *Tilia*, *Carpinus betulus*, *Abies*, *Ulmus*, *Fraxinus excelsior* and fern spores of Polypodiaceae suggests an increase of temperature that is seen in the paleotemperature record of Greenland Ice sheet-2 (GISP-2) (Blunier and Brook 2001). Probably, warming/humidity increase during these melting pulses is expressed by the open coniferous forest development. Isolated patches of these taxa must have survived in micro-environmentally favourable pockets. These data suggest that these small pockets in the Black Sea coastal mountains play an important refugial role in the survival of temperate arboreal taxa along south-eastern Europe during the Last Full Glacial (Beug 1975; Bottema 1980; Bennett et al. 1990; Tzedakis 1993; Willis 1994). Our results corroborate

Table 3. Correlation between local and regional pollen assemblage zones and subzones (modified after Filipova-Marinova (2006a)).

cal. kyrs. BP (Fig. 2)	Northerneuropean climatostratigraphy (Blytt 1876– Sernander 1908)			Regional stages and substages (Shopov 1991)	Archaeological Chronology (Todorova 1986)	Regional PAZ subzones	Pollen assemblages (Filipova- Marinova 2006)	2345		09-15		GGC18		09-10		544		11-17																																								
								Local PAZ	Pollen assemblages (Filipova- Marinova 2003b)	Local PAZ	Pollen assemblages (Table 2)	Local PAZ	Pollen assemblages (Filipova- Marinova et al. 2013)	Local PAZ	Pollen assemblages (Table 2)	Local PAZ	Pollen assemblages (Filipova et al. 1989)	Local PAZ	Pollen assemblages (Table 2)																																							
2.8	HOLOCENE			Subatlantic	New Black Sea	Iron Epoch	IX	Q-U-Al- Cb-Sa-F	8	Q-U-Al-F			6	Q-Al- Cb-U-F	6	Q-Al-U- Cb-F	6	Q-Al- Cb-U-F	6	Q-Al-U- Cb-F																																						
5.5																					Atlantic	Old Black Sea	Early Bronze Age	VIII	Q-Cb- Co-F- Cor-Ce	7	Q-Cb-Co-F	5	Q-Cb-F	5	Q-Cb-F- Co-Cor- Ce	5	Q-Cb- Co-F	5	Q-Cb- Co-F																							
8.2																																				Late Eneolithic	VII	Q-Co- Cb-U-Tr- Ce	6	Q-Co-U- Cb-Ti	4	Q-Co- Cb-U-F-	4	Q-Co-Cb- U-Ce-Tr	4	Q-Co- U-F-Cb	4	Q-Co-Cb- U-Ce-Tr										
																																																	Boreal	Neolithic	VI	b	Q-U-Co- Art	stratigraphic hiatus		3	Q-U-Art	3
11.7																																				Preboreal	a	Q-P-Art	2	Q-P-Art	2	Q-P-Art	3	Q-Co- U-Cb- Art	3	Q-Art-Ch												
13	PLEISTOCENE			Late Würm	Late Glacial	Younger Dryas	Upper- New- euxinian	V	d	Art-Ch	5	Art-Ch	3	Art-Ch	1	Art- Ch-P	2	P-Art-Ch	2	Art-Ch	2d	Art-Ch																																				
14																							Allerød	c	P-Art- Ch	4	P-Art-Ch	2	P-Art- Ch	1	Art- Ch-P	1	P-Art- Ch	2c	P-Art																							
14.3																																				Older Dryas	b	Art-Ch- Po	3	Art-Ch-Po	1	Art- Ch-P	2b	Art-Ch														
15.6																																													Bølling	a	P-Art	2	P-Art	2a	P-Art-Ch							
25.9																																																				Oldest Dryas	IV	Art- Ch-P	1	Art-Ch-P	1	Art-Ch-P

Legend: Al = *Alnus*, Art = *Artemisia*, Be = *Betula*, Cb = *Carpinus betulus*, Ce = *Cerealia*-type, Ch = *Chenopodiaceae*, Co = *Corylus*, Cor = *Carpinus orientalis*, F = *Fagus*, P = *Pinus diploxylon*-type, Po = *Poaceae*, Q = *Quercus*, Sa = *Salix*, Ti = *Tilia*, Tr = *Triticum*, U = *Ulmus*; — missing stratigraphic units.

with data of core 22-GC3 from the southern Black Sea region (Shumilovskikh et al. 2012), Ioanina (north-western Greece) (Tzedakis 1993) and Thenagi Philipon (Bottema 1980). Similar pollen spectra were found at ca. 27990 ± 300 ¹⁴C yrs BP by Frenzel (1964) at Stilfied in Austria and were related to the Paudorf Interstadial. This interstadial is also established, although less clearly and dated at 27295 ± 1120 ¹⁴C yrs BP for the Black Sea by Komarov et al. (1979). Mudie et al. (2002, 2007) recognised a Pleniglacial pollen assemblage zone with relatively low AP values suggesting a steppe-forest vegetation and moderately high precipitation in winter for Marmara Sea core MAR 95-04, with age of 29540 ± 1540 to 21950 ± 310 ¹⁴C yrs BP and in the south-western Black Sea Core MAR 98-04 which has a radiocarbon age of 33550 ± 330 ¹⁴C yrs BP (Aksu et al. 2002).

The Paleoclimate model of Peyron et al. (1998) for the Last Glacial maximum (LGM) shows that the climate in southern Europe during the Pleniglacial was characterised by extremely low temperatures and humidity throughout the year. Reconstructed temperatures for the area north of the Mediterranean Sea were lower than today: -15 ± 5 °C for the coldest month and -10 ± 5 °C for the annual mean temperature. In Greece, the available moisture was 20% lower with

a precipitation anomaly of ca. 600 ± 200 mm. Kutzbach and Webb (1993) also suggested the Full Glacial conditions in eastern Europe with extremely cold and arid climate and predicted January temperatures as low as -20 °C.

These marine deposits are found below the 30 m isobath in almost all investigated cores of the western Black Sea shelf. In the peripheral (outer) shelf zone, they form clearly defined depositional bodies of coastal or barrier type sediments at the depth of 100 to 120 m (Khrishev and Shopov 1978). Chepalyga (2002) points out that the eustatic regression of the World oceans had led to loss of the two-way connection with the Mediterranean Sea and a subsequent evaporative drop in the level of the Black Sea to a strand-line of -90 m or lower.

Regional Pollen Assemblage Zone V **15612–11788 cal. yrs BP**

This zone is distinguished in all cores studied and could be correlated with the Late Glacial/Neoeuxinian age. All stadials and interstadials were determined palynologically and four subzones were presented.

Regional Pollen Assemblage Subzone Va (*Pinus* – *Artemisia*) **15612–14295 cal. yrs BP**

Subzone Va corresponds to the Bølling Interstadial of the European Late Glacial and can be referred to as the Upper Neoeuxinian. It is clearly separated only in core AKAD 11-17 (LPASZ AKAD 11-17 2a) (Fig. 3, Tables 2, 3), but cannot be separated in core AKAD 09-10 (LPAZ AKAD 09-10 2) (Fig. 5, Tables 2, 3) because the pollen analysis in this core section is not of high resolution. The basic characteristic of the vegetation succession during this period of moderate warming is the restriction of areas occupied by steppes dominated by *Artemisia* and the existence of open forests and scattered patches with *Pinus* and *Quercus* along the coast. The contribution of the thermophilous broad-leaf arboreal taxa and the decrease of spread of the desert shrub *Ephedra distachya* suggest climate amelioration. Although some of the *Pinus diploxylon*-type pollen could be of long distance origin, these high percentages (more than 50%) suggest a local and regional expansion of *Pinus* at the expense of shrubs and herbs, as is clearly recorded. This rapid interstadial expansion testifies that *Pinus* survived along the coast during the Late Glacial period. Detached stands of some temperate arboreal taxa, such as *Quercus*, *Ulmus*, *Corylus* and *Salix*, may also have been preserved in suitable localities. Increase of *Pinus diploxylon*-type and some thermophilous pollen taxa was also reported for the Black Sea sediments by other authors (Shimkus et al. 1977; Traverse 1978b; Komarov et al. 1979) and for the Marmara Sea (Mudie et al. 2002).

Regional Pollen Assemblage Subzone Vb (*Artemisia* – *Chenopodiaceae* – *Poaceae*) **14295 – 14036 cal. yrs BP**

Subzone Vb suggests stadial environmental conditions. The available Age vs. Depth model (Fig. 2) allows this subzone to be correlated to the Older Dryas Stadial of the Würm Late Glacial and to the Upper Neoeuxinian. It is represented

in cores AKAD 09-15 (LPAZ AKAD09-151) (Fig. 7, Tables 2, 3) and AKAD 11-17 (LPASZ AKAD11-17 2b) (Fig. 3, Tables 2, 3). The Older Dryas was very short-lasting and cool. It is always hard to recognise it in sediments on the basis of paleoflora. This is the reason many authors accept Bølling and Allerød as an interstadial complex in the terrestrial pollen records from central and eastern Europe (Lang 2003). The precise distinction and correlation between cores is difficult and obscured due to the differences in both the processes of sediment formation and the succession of local vegetation between particular parts of the coast. Pollen spectra are dominated by *Artemisia* and *Chenopodiaceae*, suggesting the wide spread of xerophytic and halophytic herb communities along the coast. The percentage presence of *Pinus diploxylon*-type is slightly higher in LPAZ AKAD 09-15 1 from the Black Sea shelf for the time span 14174 to 14059 cal. yrs BP compared to other cores studied from the deep-water zone. High values of non-arboreal pollen suggest a cold and dry climate which is also confirmed by the presence of *Juniperus* and *Ephedra distachya* pollen.

Regional Pollen Assemblage Subzone Vc (*Pinus* – *Artemisia* – *Chenopodiaceae*) 14036 – 12965 cal. yrs BP

Subzone Vc is considered as an interstadial sequence analogous with the Allerød Interstadial of the Late Glacial and correlated to the Upper Neoeuxinian. It is represented in cores AKAD 09-15 (LPAZ AKAD 09-15 2) (Fig. 7, Tables 2, 3) and AKAD 11-17 (LPASZ AKAD11-17 2c) (Fig. 3, Tables 2, 3). The steppe vegetation is still rich in plant taxa, but more restricted in area, particularly the vegetation of dry habitats. The pollen record shows AP increase, particularly *Pinus diploxylon*-type pollen and presence of temperate arboreal taxa, such as *Quercus*, *Corylus*, *Ulmus*, *Salix* and *Betula*. The maximum of *Pinus diploxylon*-type pollen occurring in Core AKAD 09-15 might signal climate changes (increase of temperature and humidity). The increase in temperate arboreal pollen indicates the limited migration of some trees from the south-eastern European refugia. van der Hammen et al. (1971) and Beug (1982) also proposed the existence of refugia in southern Europe at elevations from 500 to 800 m a.s.l.

Regional Pollen Assemblage Subzone Vd (*Artemisia* – *Chenopodiaceae*) 12965 – 11788 cal. yr BP

Subzone Vd is associated with the last most significant rapid climate deterioration of the last Late Glacial Stage, i.e. the Younger Dryas Stadial and has an Upper Neoeuxinian age. This cold period is of global importance and is recognised everywhere in Europe as an episode of pronounced cooling (Berglund et al. 1994). The subzone Vd is represented in cores AKAD 09-15 (LPAZ AKAD 09-15 3) (Fig. 7, Tables 2, 3) and AKAD 11-17 (LPASZ AKAD 11-17 2d) (Fig. 3, Tables 2, 3). The reversal from interstadial towards stadial conditions occurred after 12965 cal. yrs BP, corresponding to the termination of the Allerød phase in western Europe and to the GISP-2 ¹⁸O climate record (Stuiver et al. 1995). This phase is also clearly recognised in the Marmara Sea (Mudie et al. 2002, 2007) and in Lake Van (Wick et al. 2003).

This succession reflects the expansion of xerophytic herb (steppe) vegetation. Palynological data show that, in addition to the predominant light-demanding xe-

rophytic and halophytic taxa such as *Artemisia* and Chenopodiaceae, many other taxa, such as Poaceae, *Aster*-type, *Achillea*-type, *Centaurea*, *Thalictrum*, Apiaceae and Caryophyllaceae have also participated in these steppe communities. The extremely high percentages of *Artemisia* suggest that the Younger Dryas climate of the Bulgarian Black Sea coast is analogous to that of the Last Glacial maximum. *Chenopodiaceae* is always subdominant to *Artemisia* during the Pleniglacial and the Late Glacial Stadials (Atanassova 2005; Mudie et al. 2007; Shumilovskikh et al. 2012; Filipova-Marinova et al. 2013). This confirms that Younger Dryas is the coldest and driest period along the northern Bulgarian Black Sea coast during the whole Late Glacial. Strong evidence of this climatic deterioration can be seen in the increase and continuous presence of *Juniperus* and the indicator of the cold and dry climate *Ephedra distachya*. High percentage values of *Artemisia* and Chenopodiaceae may have also been a result of the wide extent of halophytic species such as *Salsola ruthenica*, *Suaeda maritima*, *Salicornia europaea* and *Artemisia maritima* growing on the beach area and on the part of the modern shelf after the withdrawal of the sea to -100 m during the Neoeuxinian regression (Chepalyga 2002). There is a steep decline in AP, reflected by a decrease of pollen of *Pinus diploxylon*-type from 13257 cal. yrs BP onwards and restricted occurrence of almost all deciduous arboreal taxa. Stands of *Pinus*, *Quercus*, *Corylus*, *Carpinus betulus*, *Ulmus*, *Tilia* and *Betula* were sparsely distributed in favourable moisture localities in the Eastern Balkan Range (Stara Planina Mts.). This supports the hypotheses of Beug (1975) that refugia of deciduous trees would have been located at mid-altitude sites where the precipitation would have been higher than on the plains during this arid glacial period. This information is of great importance in tracing the main migration routes of these deciduous trees along the Bulgarian Black Sea coast after the last glaciation. Probably, stands of *Pinus* occupied the higher parts of the coastal plateaux, where conditions were more favorable for the growth of trees because of higher atmospheric humidity.

Multiple factors may have been important in determining the vegetation changes in this region, including climate oscillations (Cordova et al. 2009). Such a vegetation type can be attributed to the reduced pollen production under the influence of cold and dry glacial conditions (Willis 1994). Independent evidence provided by isotope analyses makes the distinction that timing and duration of the Late Glacial and Early Holocene aridity along the Black Sea and eastern Mediterranean is strongly linked with the summer insolation (Wright et al. 2003; Tzedakis 2007). Palynological records from the Black Sea region also confirm the results from climate modelling experiments of Kutzbach and Webb (1993) that summer insolation maxima override the effects of the North Atlantic circulation in the continental lowlands of the Balkans. Similar pollen assemblages appear also in other marine cores from the western Black Sea shelf and deep-water zone and show that this climate oscillation has an ambiguous signal in palynological records and is clearly apparent along the whole Bulgarian Black Sea coast (Atanassova 2005; Shumilovskikh et al. 2012; Filipova-Marinova et al. 2013). The Younger Dryas event in the western Black Sea area is also dated by the *Artemisia* maximum at ~ 10660 cal. yrs BP (Mudie et al. 2007). A large increase in non-arboreal pollen (NAP) with peaks in *Artemisia* and *Ephedra* and increased Chenopodiaceae is found in Core MAR 98-12 of the nearby Marmara Sea during the Younger Dryas (Mudie et al. 2002; Caner and Algan 2002). According to Niklewski and van Zeist (1970) and Connor et al.

(2013), aridity, rather than temperature during the glacials, seems to have been the key factor limiting lowland forest development during this steppe phase.

Regional Pollen Assemblage Zone VI (*Quercus* – *Pinus* – *Artemisia*) 11788 – 8004 cal. yrs BP

This zone could be correlated with the Preboreal-Boreal chronozone/Old Black Sea Substage and is represented in cores AKAD 09-10 (LPAZ AKAD 09-10 3) (Fig. 5, Tables 2, 3) and AKAD 11-17 (LPAZ AKAD 11-17 3) (Fig. 3, Tables 2, 3). The studied sediments with Preboreal age cannot be separated from that of the Boreal age in Cores AKAD 09-10 and AKAD 11-17, because the pollen analysis in this section is not of high resolution. This zone is marked by the abrupt change from *Artemisia* – *Chenopodiaceae* to a *Quercus* – *Pinus* – *Artemisia* assemblage. The increased values of total AP and deciduous arboreal taxa suggest an establishment of pioneer formations mainly of *Quercus* and *Pinus*, most probably in a mosaic structure. This change would be in line with the notion of Giesecke et al. (2011) that the beginning of the Holocene is a period of pronounced and frequent change in the vegetation composition. The pollen records from the Black Sea continental slope and deep-water zone suggest a forest-steppe vegetation succession. The vegetation was relatively open, based on the diversity of xerophytic and mesophytic herbs in the pollen records. Abundance of non-arboreal taxa, such as *Artemisia*, *Chenopodiaceae*, *Poaceae* and *Asteraceae* was still high and may indicate that humidity was a major limiting factor in the widespread distribution of forests along the coast or that there were still large areas of disturbed open soil. The first step in the afforestation along the western Black Sea coast began after 11788 cal. yrs BP with the rapid increase of some arboreal taxa.

The most characteristic feature for the Early Holocene vegetation palaeosuccession is the early appearance of *Quercus* as a pioneer element in open pine forests, while, in central and northern Europe, the light-demanding species *Corylus avellana* started to spread in open forests dominated by *Pinus* and *Betula* where interspecies competition was probably of little importance (Birks and Line 1993; Tallantire 2002; Finsinger et al. 2006). The example of *Corylus avellana* shows that the same species can show different behaviour with respect to its regional expansion. *Betula* does not play a prominent role along the Bulgarian Black Sea coast in contrast to high mountain areas (Bozilova and Tonkov 2000; Stefanova et al. 2006). The pollen diagrams from the southern Black Sea region (north-western Turkey) suggest greater occurrence of *Betula* during the Early Holocene than in the modern vegetation cover (Bottema 1990).

The characteristic expansion of *Quercus* is due to the increase in temperatures and humidity. Probably, different oak species, such as *Q. cerris*, *Q. frainetto*, *Q. pubescens* and *Q. polycarpa*, took part in the composition of these forests. In addition to *Quercus*, several temperate taxa, such as *Ulmus* and *Tilia*, were also present in these forests. The presence of *Ulmus* supports the assumption of Stojanov (1950) that, in the past, *Ulmus* forests were the most important components of the vegetation of the lowlands. *Carpinus betulus* is still an insignificant component of the oak forests, as well as *Corylus*, *Tilia* and *Fagus*.

The first increase of deciduous arboreal pollen, mainly of *Quercus* is dated at about 9630 ± 520 ^{14}C yrs BP at Core-544 of the deep-water zone (Filipova et al. 1989) and about 9945 ± 160 ^{14}C yrs BP at Core-149 of the nearby estuary of the

Veleka River (Filipova-Marinova 2003a). Mudie et al. (2002) also reported that *Quercus*, *Carpinus betulus* and *Ulmus* were present in the Early Holocene and began to expand after 8500 ¹⁴C yrs BP. Similar changes in vegetation composition along the coast during that time have also been documented by Atanassova (2005) and Shumilovskikh et al. (2012). Such vegetation change is classically observed for the beginning of the Holocene at the Mediterranean area (Tzedakis 2007). In Romanian Carpathians, the spread of oak forests occurred after that of *Ulmus* at about 10800 cal. yrs. BP (Feurdean et al. 2010), while, at higher elevations of Bulgarian mountains, it started together with the expansion of *Betula* forests after 11200 cal. yrs BP (Tonkov et al. 2002). Early pollen increase in *Quercus*, *Ulmus*, *Tilia* and *Acer* in marine records indicates rapid expansion of these temperate taxa during the Early Holocene, likely from local sources and suggests that they probably had Glacial refugia in the Strandzha Mountains and the Stara Planina Mountains (the Balkan Range). According to Lang (1985), it is not certain if *Quercus*, *Ulmus*, *Tilia*, *Fraxinus* and *Acer* occurred together in the mixed oak forests of Europe, because the distribution of these taxa depends on edaphic conditions and topography. Most probably, in the Bulgarian coastal region, *Quercus*, *Ulmus* and *Corylus* were distributed on the richest soils of the southern slopes and the hills of the Strandzha Mountains and the Stara Planina Mountains (the Balkan Range), while *Fagus* and *Carpinus betulus* were spread on northern slopes and along the humid ravines. The early expansion of temperate arboreal taxa and the presence of pollen grains of *Fagus*, *Rhododendron*, Ericaceae and *Juglans* support the notion of van der Hammen et al. (1971), Huntley and Birks (1983) and Bennett et al. (1990) that there were refugia of these taxa in the Strandzha Mountains during the glaciations.

The Sofular Cave (Zonguldak Province, north-western Turkey) record also suggests a fast re-vegetation with trees and shrubs at the onset of the Early Holocene (Fleitmann et al. 2009). These results are in accordance with the presumption of Leroy and Arpe (2007), that parts of the Black Sea mountains were Glacial refugia for temperate trees, which facilitated their rapid re-advance at the onset of the Holocene (11600 cal. yrs BP).

Brewer et al. (2002) consider that the climate of the Early Holocene acted as the strongest controlling factor on the spread of the oak. According to Davis et al. (2003), the Early Holocene warming and later equilibrium has been mainly modulated by increased winter temperatures. Shimkus et al. (1977) and Komarov et al. (1979) also suggest climate warming and increase of arboreal taxa along the Black Sea coast from 10737 ± 315 ¹⁴C yrs BP. Around the Marmara Sea, the amelioration of climate occurred around 10200 ¹⁴C yrs BP (Mudie et al. 2002).

Warming at the onset of the Holocene also allowed a rapid spread of oak along the Atlantic coast of Europe (Brewer et al. 2002). According to Berglund et al. (1984), such vegetation change is probably a biotic reaction of the climate improvement before about 10000 years including the rise of temperature. The delay of spreading of other arboreal species, such as *Carpinus betulus*, *Corylus*, *Fagus* and *Alnus*, along the coast was probably due to the low humidity of the Early Holocene climate.

Pinus diploxylon is noted as the major contributor to the Early Holocene pollen assemblages (Mudie et al. 2002). However, along the Bulgarian Black Sea coast, percentage values of *Pinus diploxylon*-type declined, while the deciduous arboreal taxa expanded their presence in the pollen spectra. Taking into account the over-representation of *Pinus* pollen in modern surface samples from the western

and central Balkan Range (Stara Planina Mts) (Filipovitch et al. 1997) and from the Black Sea coast (Pardoe et al. 2010), the high values of *Pinus* pollen could be partly due to the long distance transport. The formation of isolated stands of *Pinus* on higher localities on the Bulgarian Black Sea coast could not be excluded.

A rapid and very short-term steep decline of arboreals is established in marine core AKAD 11-17 from the deep-water zone at 8500 to 8300 cal. yrs BP (70–65 cm) and in core AKAD 09-10 from the continental slope at 8253 cal. yrs BP at the transition of Boreal and Atlantic chronozones (130 cm) (Figs 3, 5). This event could be caused by the changes in climate parameters or short climate extrusion that would trigger synchronous shifts in vegetation composition. For the first time, evidence for such an abrupt cooling event was identified in the pollen diagram from Core GGC-18 from the south-western Black Sea continental slope (Filipova-Marinova et al. 2013). This short-term arid phase in Black Sea coastal palaeoclimate is confirmed by a decrease in arboreal pollen, particularly of *Quercus* and *Ulmus* simultaneously with the increase of *Artemisia*, presence of the indicator of cold climate *Ephedra distachya* and low sedimentation rate between 8500 and 8253 cal. yrs BP. This event should be considered as a vegetation response to the “8200 yrs BP cold event” (Magny et al. 2003; Alley and Ágústssdóttir 2005; Bahr et al. 2005; Le Grande et al. 2006) as other pollen diagrams from Germany and Finland also show such synchronous pronounced short decline of AP between 8500 and 8300 cal. yrs BP (Giesecke et al. 2011). According to the pollen-based temperature reconstructions, a significant drop in average winter temperatures in the order of 4 °C has been estimated during this rapid climate event, while summer temperatures appear to have been comparable to those currently prevailing in the north-western Carpathians (Feurdean et al. 2008). In Thenagi Philippon (northern Greece) during the “8200 yrs BP event”, a significant reduction in tree pollen is observed, that is representative of a decline in winter temperatures of more than 4 °C caused by perturbation of North Atlantic circulation (Pross et al. 2009). Tinner and Lotter (2001) consider this event as a very rapid synchronous response of southern European vegetation to suborbital climate change. In the Balkan Region, this rapid climate change was also identified in the Holocene sequences from the Carpathians (north-western Romania) (Feurdean et al. 2010), Thenagi Philippon (north Greece) (Müller et al. 2011) and Lake Prespa (Macedonia) (Panagiotopoulos et al. 2012). In the Bulgarian high altitudes in the Rila Mts., this event is manifested by the decline of arboreal pollen accumulation rate to ca. 500 grains cm²/yr¹ at 8230 cal. yrs BP, particularly by the decline in *Pinus diploxylon*-type and less of *Betula* (Tonkov et al. 2016). The decrease in temperate forests most probably reflects a decrease in humidity (Combourieu Nebout et al. 2009; Dormoy et al. 2009). A shift in moisture regime led to a shift in the vegetation composition (Tinner and Lotter 2006). According to Roberts et al. (2011), deciduous oak species require high soil moisture during the summer, probably a decrease in soil moisture level at summer contributing to the *Quercus* declining trend observed in the cores studied.

Regional Pollen Assemblage Zone VII

(*Quercus* – *Corylus* – *Carpinus betulus* – *Ulmus* – *Triticum* – *Cerealia*)

8004 – 5483 cal. yrs BP

This RPAZ can be correlated to the Atlantic chronozone of the Middle Holocene that corresponds to the Old Black Sea Substage. It is represented in cores

AKAD 09-10 (LPAZ AKAD 09-10 4) (Fig. 5, Tables 2, 3) and AKAD 11-17 (LPAZ AKAD 11-17 4) (Fig. 3, Tables 2, 3). The temperate deciduous arboreal pollen taxa reach their maximum, indicating rapid spread of stable mixed oak forests. Their maximal distribution is recorded at 6417 cal. yrs BP in LPAZ AKAD 11-17 4 and at 5745 cal. yrs BP in LPAZ GGC18 4. The high values of AP suggest that forests become denser. *Quercus* appears to be the major arboreal taxon in the mixed oak forests with abundant *Corylus*, *Carpinus betulus*, *Ulmus*, *Fraxinus excelsior*, *Tilia* and *Acer*. The optimal climate conditions as well as moisture balance of the Black Sea Region were determining factors that stimulated the extensive spreading of these forests. This expansion of mixed oak forests was also attributed to the rise of the Black Sea level during this period resulting in an increase in atmospheric moisture content. According to Tonkov and Bozilova (1995), high humidity on the Balkan Peninsula was reached after 8000 ¹⁴C yrs BP and the climate was determined by the transport of air masses from the Atlantic Ocean. The presence of the indicator taxa, such as *Hedera* and *Humulus/Canabis*, confirms an increase in humidity and rise in mean annual temperatures.

Corylus expanded in the local stand mainly at the expense of *Ulmus* and became widespread from 7584 to 5483 cal. yrs BP. This taxon has high pollen productivity in open areas. Pollen data suggest the great extent of monodominant communities of *Corylus* in open areas, but probably also as an undergrowth of the oak forests. The maximum percentage values of *Corylus* could be associated with a short-term fluctuation of climate parameters, but also with a clearance of mixed oak forests for enlargement of cultivated areas along the coast as is seen by the synchronous maximum values of *Cerealia*-type pollen (Filipova-Marinova 2006a). Interspecies competition could not be excluded, because the rapid reduction of *Corylus* values corresponds to the beginning of the continuous curves of *Carpinus betulus* and *Fagus* in all pollen diagrams from the Bulgarian Black Sea coast from the end of Atlantic around 5500 cal. yrs BP. The increase of *Carpinus betulus* started after 6417 cal. yrs BP in LPAZ AKAD 11-17 4 (Fig. 3). The first regular occurrence of *Fagus* suggests the presence of this taxon at about 9000 cal. yrs BP. The expansion of *Fagus* started as early as 8283 cal. yrs BP (8355 ± 75 ¹⁴C yrs BP) (Filipova-Marinova 2003b) at the southern part of the Bulgarian Black Sea coast, while at the northern Bulgarian Black Sea coast, the areas occupied by *Fagus* expanded after 6500 cal. yrs BP (LPAZ AKAD11-17 4) reflecting favourable conditions for its spreading and it started to be better represented in suitable localities at lower altitudes. The maximum of *Fagus* occurred around 3260 cal. yrs BP (3070 ± 100 yrs BP) (Filipova 1985). Nowadays, communities of this species could be found in the Eastern Balkan Range at altitudes between 170 and 450 m a.s.l. (Bondev 1991). Another broad-leaf tree pollen type in the diagrams is *Acer*. A regular occurrence of *Acer* pollen from 7750 cal. yrs BP is indicative of a local presence of this taxon.

The presence of *Alnus*, together with several occasional pollen grains of *Hedera*, confirms the increase in humidity and temperature along the coast. Submediterranean elements such as *Carpinus orientalis* and *Fraxinus ornus* also occurred near the coastline. *Carpinus orientalis* appeared and probably occupied some areas after the degradation of mixed oak forests due to a human impact that influenced the natural vegetation. The first occurrence of *Juglans* is registered at 7584 cal. yrs BP in LPAZ AKAD 11-17 4. The earliest appearance of several occasional pollen grains of *Juglans* along the southern Bulgarian

Black Sea coast during the Holocene is registered for Preboreal, ca. 10000 cal. yrs BP (Filipova-Marinova 2003a), confirming the possible relic origin of this taxon in the Balkan Peninsula (Bottema 1980).

The first appearance of pollen of anthropophytes, such as *Cerealia*-type, *Triticum*, *Plantago lanceolata* and *Polygonum aviculare*, coincides with the decline of *Corylus* and *Ulmus*, marking human impact during the Late Eneolithic period, 6790–6320 cal. yrs BP (Bozilova and Beug 1992, 1994; Filipova-Marinova and Bozilova 2002, 2003). Human impact was significant along the western Black Sea coast as reflected in pollen diagrams from the Bulgarian Black Sea coastal lakes (Todorova 1986; Bozilova and Filipova 1991; Bozilova and Beug 1994). Terrestrial pollen records from the eastern Black Sea coast reveal anthropogenic impact starting at 4000 ¹⁴C yrs BP (Connor et al. 2007).

Regional Pollen Assemblage Zone VIII

(*Quercus* – *Carpinus betulus* – *Corylus* – *Fagus* – *Carpinus orientalis* – *Cerealia*)
5483 – 2837 cal yrs BP

The characteristic vegetation succession and the available Age vs. Depth model allow correlation of this RPAZ to the Subboreal chronozone of the Middle Holocene that also corresponds to the Old Black Sea Substage. It is represented in cores AKAD 09-10 (LPAZ AKAD 09-10 5) (Fig. 5, Tables 2, 3) and AKAD 11-17 (LPAZ AKAD 11-17 5) (Fig. 3, Tables 2, 3). The pollen record shows that mixed oak forests still dominate, but a change in the forest composition is registered after 5483 to 2857 cal. yrs BP. The most prominent feature for this zone is the increase of *Carpinus betulus*. The maximum of *Carpinus betulus* pollen is also dated at 5680 ± 65 ¹⁴C yrs BP in the Arkutino Lake (Bozilova and Beug 1992) and at 5650 ± 100 ¹⁴C yrs BP in the Shabla-Ezeretz Lake (Filipova 1985). According to Filipovitch et al. (1998), this species formed a separate belt on higher areas in the Balkan Range at about the same time. The hornbeam belt was also common on eastern Carpathians during the Subboreal and dated to around 4210 ± 35 ¹⁴C yrs BP (Tantau et al. 2011). The presence of *Corylus*, *Ulmus*, *Fraxinus excelsior*, *Tilia* and *Acer* suggest that these taxa also appeared in the mixed oak forests. The decline of *Corylus* started at the same time as *Fagus* and *Carpinus betulus* became established around 5500 cal. yrs BP. The expansion of *Fagus* during the Subboreal must have been triggered by an external factor. This factor may have been climatic change or human influence which started to increase at least in lowland areas. Forests of *Fagus orientalis* expanded in the moist ravines of the Strandzha Mountains (Filipova-Marinova 2003a), that is also reflected in marine sediments from cores studied. The local restriction of *Ulmus* is probably connected to the *Fagus* expansion which may have out-competed *Ulmus* within the local forest stand. The decrease of *Ulmus* and the increase of *Carpinus orientalis* is due to the destructive human activities during the Early Bronze Age (3200–2600 yr BP) (Todorova 1986) that is confirmed by the increase of anthropogenic indicators, such as *Cerealia*-type, *Triticum*, *Plantago lanceolata* and *Polygonum aviculare*.

Regional Pollen Assemblage Zone IX

(*Quercus* – *Ulmus* – *Alnus* – *Carpinus betulus* – *Salix* – *Fagus*)
2837 cal. yrs BP – pre-industrial time

This RPAZ can be correlated with the Subatlantic chronozone of the Late Holocene and coincides with the New Black Sea Substage. It is represented in cores AKAD 09-10 (LPAZ AKAD 09-10 6) (Fig. 5, Tables 2, 3) and AKAD 11-17 (LPAZ AKAD 11-17 6) (Fig. 3, Tables 2, 3). There is a slight reduction of pollen of deciduous arboreal taxa although they are still dominant. Modern plant communities began to form after 2837 cal. yrs BP. The decrease in mixed oak and hornbeam forests at the beginning of Subatlantic is probably due to the human impact during the Iron Epoch, that is also confirmed by the persistent presence of *Cerealia*-type and *Triticum*, as well as anthropophytes *Plantago lanceolata* and *Polygonum aviculare*. In areas with erosion, mixed oak forests were replaced by communities of *Carpinus orientalis* and *Quercus pubescens*. The increase of *Corylus* may also reflect deforestation. However, climate-driven changes cannot be excluded. Prominent cooling and increase in humidity are recorded in northern Europe from 2800 to 2500 cal. yrs BP that broadly coincides with the transition of Subboreal to Subatlantic. According to van Geel and Berglund (2000), the cooling during the last 3000 years can be related to the abrupt decrease in solar activity around 2900–2800 cal. yrs BP. Probably the increase of humidity and cooling of the climate along the Black Sea coast were the main reasons for the specific succession and increased abundance of *Alnus*, *Fraxinus excelsior*-type and *Salix* along with lianas and formation of flooded riparian forests ('Longoz') lining the river valleys along the Black Sea coast, dominated nowadays by *Alnus glutinosa*, *Fraxinus oxycarpa*, *Ulmus minor*, *Carpinus betulus* and *Quercus pedunculiflora*.

Dinocyst assemblages

For a more correct and detailed reconstruction of the natural environment of the Black Sea, the changes in the relative abundance of dinoflagellate species and their assemblages recorded in three cores from the NW Black Sea were studied (Fig. 1) since marine cores are very sensitive and indicative of changes in environmental parameters, such as sea surface temperature (SST), sea surface salinity (SSS) and nutrient variability (Popescu et al. 2009). Two of the cores studied AKAD 09-10 (Fig. 6, Table 2) from the continental slope and AKAD 11-17 (Fig. 4, Table 2) from the deep-water zone, provide long and well-dated continuous Late Quaternary records from the Black Sea spanning the Pleniglacial, Late Glacial and Holocene, while Core AKAD 09-15 (Fig. 8, Table 2) from the peripheral shelf zone represents only a Late Glacial record due to removal of Holocene sediments by strong bottom currents (Dimitrov 1979). Two distinct local dinoflagellate cyst (dinocyst) assemblage zones (LDAZ) were recorded: one dominated by endemic stenohaline freshwater/brackish-water species *Pyxidinosia psilata* and *Spiniferites cruciformis* (LDAZ 1) and a successive one composed of euryhaline brackish to hypersaline species (LDAZ 2). The second zone is subdivided into two subzones (LDASZ 2a and LDASZ 2b). Variations in dinocyst assemblages from the studied cores are very similar and comparable to those studied previously from the western Black Sea for the same period (Wall et al. 1973; Wall and Dale 1974; Mudie et al. 2001, 2002, 2004, 2011; Filipova-Marinova 2006b; Marret et al. 2009; Verleye et al. 2009; Shumilovskikh et al. 2013).

Regional dinocyst assemblage zone 1 (RDAZ 1)
(*Pyxidinopsis psilata* – *Spiniferites cruciformis*)
25903 – 7668 cal. yrs BP

This zone comprises sediments deposited between 25903 and 7668 cal. yrs BP and could be correlated to the Late Pleniglacial, Late Glacial and Early Holocene (Neweuxinian stage). This assemblage is represented in all three cores studied: AKAD 11-17 from 19546 to 7668 cal. yrs. BP (230–59 cm) (Fig. 4, Table 2); AKAD 09-10 from 25903 to 7663 cal. yrs BP (240–128 cm) (Fig. 6, Table 2); AKAD 09-15 from 14147 to 10906 cal. yrs BP (377–10 cm) (Fig. 8, Table 2). The zone is characterised by a very low number of species and the dominance of two stenohaline freshwater/brackish-water dinoflagellate species *Pyxidinopsis psilata* and *Spiniferites cruciformis* accompanied by fresh-water algal taxa, represented by coenobia of the colonial chlorococcalean algae *Pediastrum* and rarely *Botryococcus* and *Achomosphaera* cf. *andalusiensis*. The spherical *Pyxidinopsis psilata* is a well-known brackish-water species and an important indicator of cooler SST during glacial periods (Matthiessen and Brenner 1996). However, Brenner (2001) found that occurrence and abundance of *P. psilata* of annual varves of Baltic Sea sediments is controlled by additional as yet unknown factors other than salinity. Based on modern distribution of *P. psilata*, Zonneveld and Pospelova (2015) considered this species as a euryhaline temperate one with wide environmental parameter range considering SST and SSS. The ecological affinities and the significance of *Spiniferites cruciformis* as a crucial indicator of sea surface salinity (SSS) has been an ongoing debate not only recently, but since its discovery. It has been defined classically as a fresh-water/brackish-water species, whose salinity appears not to have exceeded 7‰ (Wall and Dale 1974). Kouli et al (2001) identified *S. cruciformis* in lacustrine Late Glacial sediments and suggested that *S. cruciformis* is essentially a freshwater taxon with morphological variations of the cysts that only partly may be linked to salinity variations. Eaton (1996) suggests that the cruciform shape of *S. cruciformis* must be a stress effect of low salinity waters of less than 12‰. In modern surface sediments, *S. cruciformis* and *P. psilata* have been recorded only in the Caspian and Aral Seas at SSS of around 12–13‰ (Marret et al. 2004) and *P. psilata* in the Baltic Sea at salinity of 12‰ (Yu and Berglund 2007). Based on analogous correlations, most of the authors suggest a maximum SSS of around 12‰ during the lacustrine stage of the Black Sea (Wall et al. 1973; Wall and Dale 1974; Mudie et al. 2001, 2002, 2004; Filipova-Marinova 2006b; Marret et al. 2009; Verleye et al. 2009; Shumilovskikh et al. 2013). The data from our cores revealed that, in addition to the dominant stenohaline brackish-water dinoflagellate species *P. psilata* and *S. cruciformis*, the well-known freshwater indicators, such as *Pediastrum boryanum* var. *boryanum*, *P. simplex* var. *sturmii*, *P. kawraskyi*, *P. integrum* and rare *Botryococcus*, *A. cf. andalusiensis* and acritarch *Multiplicasphaeridium*-type, are also present even in modest percentages (note that dinocysts and algae percentages were calculated based on the pollen sum). The investigation of ecological affinities of *Pediastrum* indicates that this taxon is common to rare at a salinity of about 5‰ (Hiscott et al. 2007) although records from brackish habitats are also documented (Brenner 2001). Detailed studies of surface sediment samples from the Baltic Sea show that the dominant species *P. boryanum* var. *boryanum* and *P. kawraskyi* are stenohaline species associated with a wide

range of temperature and trophic conditions, dominant in salinity from 6–8‰ (a full range is 5–9‰), *P. simplex* occurring in sediments of less than 3–5‰ salinity while *Botryococcus* is a more south-tolerant taxon sometimes living in brackish waters (Matthiessen and Brenner 1996). *Achomosphaera* cf. *andalusiensis* is a species of cold north-temperate climate and low salinity melt-water fluvial conditions (Harland 1983). All these data support our estimation that the limit of SSS for the Neweuxinian stage of the Black Sea falls in the range of 5–12‰.

The dinocyst record shows the low abundance or absence of stenohaline brackish-water species *P. psilata* from 19 to 15.5 ka yrs BP in core AKAD 11-17 and to 17.1 ka yrs BP in core AKAD 09-10 probably connected with the lack of a favourable environment for the growth of this species due to the strong melt-water and terrigenous input during that time. *Pediastrum boryanum* var. *boryanum* (considered a good indicator of freshwater input) has cyclical abundance associated with the deposition of four red-brown clay layers between 19 and 14 ka BP. The red-brown layers have been previously distinguished and dated from the north-western Black Sea shelf from 18.3 to 15.5 ka BP, in several pulses (Major et al. 2002; Bahr et al. 2006). Four red-brown layer intervals were identified and dated by Soulet et al (2016) from 17.2 to 14.8 ka BP. From isotopic and geochemical proxies, Denton et al. (2010) argue that the deposition of the red-brown layers was linked to major melting phases of European ice, drained by the north-western Danube and Dnieper Rivers in response to the climate warming observed after the end of the Last Glacial Maximum (LGM) from 21 to 18 ka BP. Bahr et al. (2005) also indicate four major episodes equivalent to four layers of Caspian water spilling into the Black Sea. According to Major et al. (2002), it is difficult to support a direct northern source for the red-brown layers associated with the European melt-water event. During the time of the red-brown layers' deposition, the Scandinavian Ice sheet dammed large lakes and diverted rivers and melt-water drainage southwards towards the River Volga and into the Caspian Sea. These melt-waters caused the Caspian Sea to overflow over the Manych Depression (+20 m a.s.l.) into the Black Sea (Mangerud et al. 2004). Bahr et al. (2005) assume that these sediments have been transported to the shelf and the slope by strong surface currents such as the present-day 'Rim Current' gyre. The occurrence of acritarch *Glomus*-type 207 in the sediments provides evidence for terrigenous input and erosional rate increase during the deposition of these red-brown layers. The decrease in the freshwater algae *Pediastrum* is marked between 14259 and 14036 cal. yrs BP. According to its stratigraphic position at the Older Dryas sediments, it may reflect a drier with reduced river input and/or cooler climate at that time. The increase of *P. psilata* and *S. cruciformis* during the interstadials Bølling and Allerød, identified in dinocyst record of core AKAD 11-17, indicates increased phytoplankton activity and rather brackish Black Sea waters during that time, characterised by a marked increase in temperate arboreal pollen suggesting warmer and humid conditions along the Black Sea coast. The upward increase of *P. psilata*, *S. cruciformis* and *P. boryanum* var. *boryanum* between 13257 and 11072 cal. yrs BP indicates Younger Dryas SST colder than during the Bølling/Allerød in agreement with the pollen record of this core and other cores from the surrounding regions (Bottema et al. 1995; Mudie et al. 2002; Filipova-Marinova, 2003b), as well as with the return to almost LGM values of $\delta^{18}\text{O}_{\text{prec}}$ established by Bahr et al. (2006). The maximum relative abundance of *P. psilata* up to

94% in the Early Holocene record from core AKAD 11-17 is of considerable interest. Similar abundance of *P. psilata* was also found in most records from the north-western Black Sea, for example, 93–97% in core MO2-45 (Marret et al. 2009); 91–97% in core 22-GCC3 (Shumilovskikh et al. 2013); 92% in core GeoB7625-2 (Verleye et al. 2009). The explanation of why *P. psilata* considered a cool brackish-water species shows maximum relative abundance during the Early Holocene is complicated. Preboreal and Boreal chronozones of the Early Holocene are characterised by warming and humidity increase, that is previously stated in pollen records (Komarov et al. 1979; Mudie et al. 2007; Filipova-Marinova et al. 2013) and in the varved $\delta^{18}\text{O}$ paleo-term records from the Sofular Cave that tracks the isotope signature of Black Sea surface water (Göktürk et al. 2011). During the Early Holocene, characterised by a warmer climate, the stenohaline freshwater/brackish-water species *P. psilata* that have a preference for warmer temperatures and ice-free conditions (Zonneveld and Pospelova 2015), together with *S. cruciformis*, demonstrate their ecological optimum in growth concerning SST reaching maximum relative abundance between 11072 and 8638 cal. yrs BP. This maximum was interrupted by an abrupt significant short-term decrease in the relative abundance of *P. psilata* which reached values close to those characteristic of glacial periods (from 84–20%), as well as *S. cruciformis* (from 21–3%). This shift, centring between 8500 and 8300 cal. yrs BP in the deep-water core AKAD 11-17, is considerable and reflects a strong cooling of climate. This episode could be attributed to a marked short-term (with a duration of about 200 years) climate deterioration against the background of the climate amelioration during the Early Holocene. This event was also revealed in the same core by pollen data, particularly based on ecological requirements of the vegetation, represented by the ratio of relative abundance of thermophilous arboreal taxa and steppe elements including cold-resistant and heterophyllous taxa. The pollen-driven decrease in temperatures correlates with the decrease in phytoplankton productivity. The same cooling phase was previously assigned in sequence of GGC-18 from the south-western Black Sea continental slope indicating the complexity of environmental changes throughout the Basin (Filipova-Marinova et al. 2013) and confirming that the climate of the Early Holocene acts as the strongest controlling factor (Brewer et al. 2002). Bahr et al. (2006) also established that prevailing high temperatures during the Early Holocene led to authigenic calcite precipitation through increased phytoplankton activity, interrupted by the ‘8.2 ka cold event’. The findings reported above represent the regional expression of the well-known in the Northern Hemisphere ‘8.2 ka cold event’ in the Greenland $\delta^{18}\text{O}$ ice which is commonly linked to a melt-water-related perturbation of the Atlantic Meridional Overturning Circulation (AMOC) (Magny et al. 2003; Alley and Ágústssdóttir 2005; Bahr et al. 2005; Le Grande et al. 2006) and associated collapse of oceanic northward heat transport (Ellison et al. 2006). This climate anomaly is also confirmed in the Aegean Region by multi-proxy studies. Early to Middle Holocene season-specific SST and $\delta^{12}\text{O}$ seawater, based on dinocyst and foraminiferal records established in marine sediments revealed a prominent short-term (approximately 150 yrs) cooling event in the central Aegean Sea centred on 8200 cal. yrs BP, coeval to the 8.2 ka BP cold event (Marino et al. 2009). Pollen record from Thenaghi Philippon (NE Aegean Sea) provides evidence for a massive climate-induced turnover in terrestrial ecosystems of the Aegean Region

associated with the 8.2 cal. ka BP cold event as a response to the North-Atlantic thermohaline circulation slowdown (Pross et al. 2009). Using a phytoplankton-based SSS record, based on the *Emiliania huxleyi* transfer function, Herrle et al. (2018) found a reduced outflow of low salinity waters from the Black Sea into the north Aegean Sea corresponding to the 8.2 cal. ka BP cold event that was caused by cooler and drier climatic conditions over Europe. All these data support the statement that high amplitude temperature anomaly linked to the 8.2 cal. ka cold event may have also occurred in lower latitudes much further in the southerly direction than previously assigned. The Black Sea like the Aegean Sea is sufficiently distant and isolated from the North Atlantic not to be directly affected by its oceanic circulation, therefore, signal transmission must have been atmospheric (Marino et al. 2009). The 8.2 cal. ka cold event in many ways mimics the distribution and anomaly type of the Younger Dryas. It is marked, in general, by cooling with summer-time values in the order of 1°C by a strong shift in vegetation (Alley and Ágústsdóttir 2005).

Regional dinocyst assemblage subzone 2a (RDASZ 2a)

**(*Lingulodinium machaerophorum* – *Spiniferites belerius* – *Spiniferites bentorii*)
7668 – 2837 cal. yrs. BP**

A prominent change of the composition of dinocyst assemblages from fresh-water/brackish-water is observed at the boundary of LDAZ AKAD 11-17-1 and LDAZ AKAD 11-17-2a. The abrupt decrease of stenohaline freshwater/brackish-water species *S. cruciformis* and *P. psilata* at 7668 cal yrs BP indicating, according to Mudie et al. (2001), the inability of these species to survive the abrupt salinity change to values as high as 10–12‰ (Deuser 1972) or even 18‰ (Wall and Dale 1974) was followed upward by a gradual increase of euryhaline marine species. The dinoflagellate cyst assemblage was dominated by euryhaline marine species, such as *Lingulodinium machaerophorum*, *Spiniferites belerius*, *Spiniferites bentorii* and acritarch *Cymatiosphaera globulosa* and is characterised by high species diversity. The change of assemblage occurs coincidentally with the lithological change from banded lutite to sapropel which has been dated also at 7668 cal. yrs BP. Modern marine conditions, influenced by Mediterranean waters, were detected after 6417 cal. yrs BP, when an abundance of Mediterranean-related species *Operculodinium centrocarpum*, *Spiniferites mirabilis* and acritarch *Mychistidium* (occurring in hypersaline waters) along with euryhaline heterotrophic species, such as *Brigantedinium cariacoense*, *Echinidinium transparantum* and *Polykrikos kofoidii*, occurred. The immigration of marine species to the north-western Black Sea zone from 7668 to 6417 cal. yrs BP indicates a progressive increase in salinity due to more open connection with the Mediterranean. All these species are characteristic components of climate amelioration in Quaternary sequences. Such dinoflagellate cyst assemblages tolerate salinity values of 17–9‰ (Deuser 1972). The isotopic salinity estimates are in close agreement with the present day SSS of 18‰ (Mudie et al. 2002). The recorded sporadic occurrence of acritarchs, such as *Hexasteria problematica* and Fungal spores *Sordaria*-type, *Cercophora*-type 207 and *Ascospores*-type 121 in the studied records, appeared to be the best index of terrigenous input from soil erosion and markers of farming practice (Mudie et al. 2002). The most abundant euryhaline species *L. machaerophorum*

responds to the amelioration of climate and shows three peaks in the record of core AKAD 11-17: at 5016, 3459 and 1436 cal. yrs BP and in the core AKAD 09-10 at 220, 190 and 140 cm. These peaks could be related to the increased SST, SSS, a stratified water column (for instance, calm periods between upwelling events) and nutrient input due to the increased human activity during the Late Eneolithic, Early Bronze Age and Iron epoch along the Black Sea coast, confirmed also by pollen data. According to Mudie et al. (2011), blooms of *L. machaerophorum* cysts may indicate water-column stratification and nutrient enrichment more strongly than either salinity or sea level. Peaks of another characteristic component of climate amelioration, such as *Cymatiosphaera globulosa*, are synchronous with those of *L. machaerophorum* and also reflect mainly nutrient levels and stratification of the water column. The first appearance of *Peridinium ponticum*, a species related geographically to the Black Sea, is recorded from 6417 cal. yrs BP. This species is considered a good proxy for the reconstruction of Holocene salinity variations since its relative abundance fluctuates asynchronously with *L. machaerophorum* with long processes (Mudie et al. 2011).

Regional dinocyst assemblage subzone 2b (LDASZ 2b)
(*Lingulodinium machaerophorum* – *Spiniferites ramosus* – *Peridinium ponticum*)
2837 cal. yrs. BP – pre-industrial time

The composition of the Late Holocene LDASZ AKAD 11-172b is identical to that of LDASZ AKAD 11-17-2a, but the decrease in the relative abundance of almost all marine euryhaline species since 2837 cal. yrs BP is noticeable. The increase in abundance of species that tolerate low-salinity water conditions, such as *P. ponticum* and *S. ramosus*, indicate certain freshening. Since *P. ponticum* is a heterotrophic species (Dale 1996), nutrient availability also influences its abundance (Verleye et al. 2009) as recorded by pollen data, particularly by the increase in human activity indicators. The sporadic occurrence of freshwater algal species *P. boryanum* var. *boryanum* and *P. simplex* var. *sturmii*, as well as *Spirogyra* and *A. cf. andalusiensis*, suggests increasing river input associated with the cooling of climate and increase of humidity confirmed by pollen data from the studied cores. The period from 2800 to 2500 cal yrs BP coincides with a prominent cooling and increase of humidity in north Europe (Wanner et al. 2008). According to van Geel and Berglund (2000), the cooling in the Third millennium BP can be related to the abrupt decrease in solar activity around 2900 to 2800 cal. yrs BP. Freshening of the Black Sea surface water during the Late Holocene after 2500 cal yrs BP was previously assigned in the Core GGC-18 of the south-western Black Sea by Filipova-Marinova et al. (2013). Decrease in the abundance of fully marine dinoflagellate species and occurrence of the brackish-water indicator *P. ponticum* indicates seawater freshening after 2500 cal. yrs BP, also recorded in core 22-GC3 (Shumilovskikh et al. 2013). Substantial freshening of the Black Sea surface waters from 29 to approximately 19‰ after 3000 cal. yrs BP is evidenced by lower δD values of C^{37} alkenones produced by haplophyte algae *Emiliana huxleyi* (van der Meer et al. 2008). Additionally, combined lipid biomarkers and fossil DNA analyses of alkenones of *E. huxleyi* from the GGC-18 sediment core indicate a gradual cooling from 19–15 °C after 2570 cal. yrs BP (Coolen et al. 2009).

Conclusions

Vegetation successions and environmental changes along the north-western Black Sea coastal area during the last 26000 years were reconstructed by multi-proxy analysis including radiocarbon dating of sediments from three new marine cores. The following main conclusions from this study are: (1) The coastal landscape during the Late Pleniglacial (25903–17092 cal. yrs BP) was dominated by steppe vegetation composed of *Artemisia*, *Chenopodiaceae*, *Poaceae* and other cold-resistant and heliophilous herbs suggesting cold and dry environments. Sparse stands of *Pinus* and *Quercus*, partly enlarged during the melting pulses (19.2–14.5 cal. ka BP) and during the Late Glacial interstadials Bølling and Allerød reflecting warming and humidity increase. (2) During the Younger Dryas (13257–11788 cal. yrs BP), enlargement of steppe vegetation dominated by *Artemisia* and the shrubland of *Juniperus-Ephedra* indicates return to the coldest and driest climate. (3) In the Early Holocene (Preboreal-Boreal) (11788–8004 cal. yrs BP), pioneer forests of *Quercus* with groups of *Ulmus*, *Tilia*, *Alnus* and *Betula* spread and clearly confirm the presence of refugia of these taxa in the coastal mountains and their rapid migration due to the climate warming. (4) The short-term decline of arboreal pollen, particularly manifested by *Quercus*, between 8.5–8.3 ka BP can be explained as a vegetation response to the known in north Atlantic region ‘8.2 ka cold event’. This climatic oscillation is confirmed for the second time in Black Sea sediments. (5) During the Atlantic chronozone (8004–5483 cal. yrs BP), species-rich mixed oak temperate deciduous forests developed in the lowlands following climate optimal conditions (high humidity and increased mean annual temperatures). (6) During the Subboreal chronozone (5483–2837 cal. yrs BP), mixed oak forests dominate alongside a slight enlargement of *Carpinus betulus*. (7) During the Subatlantic chronozone (2837 cal. yrs BP – pre-industrial time), a specific vegetation succession manifested by the increased abundance of *Alnus*, *Fraxinus excelsior* and *Salix* along with lianas and the formation of flooded riparian forests (e.g. ‘Longoz’) lining the river valleys along the Black Sea suggests a climate shift (an increase of humidity and a cooling of the climate). (8) The first indications of farming and other human activities along the Black Sea coast were recorded during the Late Eneolithic (6790–6320 yrs BP). (9) Two main dinoflagellate cyst assemblages were distinguished: one dominated by stenohaline freshwater/brackish-water species and the successive one dominated by euryhaline marine species. (10) During the Early Holocene, *Pyxidinoopsis psilata* revealed a wide ecological range and demonstrated its ecological optimum of growth concerning the increased sea surface temperature reaching a maximum relative abundance at 9475 cal yrs BP. (11) An abrupt short-term cooling centred between 8.5 and 8.3 ka BP associated with the ‘8.2 ka cold event’ is evidenced by an abrupt decline in the abundance of *P. psilata* and *Spiniferites cruciformis* to values close to those characteristic for the Younger Dryas. This climate oscillation is described for the first time in dinocyst records from Black Sea sediments (Core Akad 11-17). This finding confirms that the high amplitude temperature anomaly, associated with the ‘8.2 ka cold event’ may have also occurred in a southern direction possibly through atmospheric transmission of the signals. (12) The change in the composition of dinocyst assemblages occurred at 7668 cal yrs BP. The abrupt disappearance of freshwater/brackish-water species *Pyxidinoopsis psilata* and

Spiniferites cruciformis was followed upwards by a gradual increase in euryhaline marine species *Lingulodinium machaerophorum*, *Spiniferites belerius*, *S. bentorii* and acritarch *Cymatiosphaera globulosa*. (13) A certain freshening of the Black Sea waters after 2837 cal. yrs BP has been established.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Data availability

All of the data that support the findings of this study are available in the main text.

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